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Diffraction in Accelerators, Colliders
And QCD*

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ABSTRACT

Recent accelerator results on diffraction are reviewed and argued to demonstrate unambiguously that diffraction is, in first approximation, described by a single Regge pole with unit intercept. The corresponding theoretical asymptotic predictions of Critical Pomeron Reggeon Field Theory are reviewed with the anticipation that they will be seen in diffraction experiments at the CERN and FERMILAB $\bar{p}$-p colliders. The earliest collider results are argued to be very encouraging. Finally a theoretical study of diffraction in gauge theories is presented which concludes that if all Critical Pomeron phenomena are confirmed at the colliders then strong interactions should be described by SU(3) gauge theory containing the maximum number of quarks consistent with asymptotic freedom.

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Introduction

At top accelerator energies and through the ISR energy range diffraction is at least 95% of total cross-sections while non-diffractive contributions are decreasing as an inverse power of the energy. As a result we expect that at the CERN and FERMILAB $\bar{p}$-p colliders strong interactions will be entirely diffractive apart, of course, from the very rare processes for which most experiments will be searching. The earliest results from the CERN $\bar{p}$-p collider have already indicated that the bulk production process (producing all diffractive cross-sections) is so overwhelming that rare processes may be extremely difficult to detect. The general picture is of large fluctuations of quantities (multiplicities for example) which in the average simply extrapolate logarithmically from the ISR energy range.

This talk was originally prepared to argue for the importance of diffraction experiments at colliders before the earliest results were available. Since I believe that these results strongly reinforce the case I wished to make I shall make reference to them throughout this written version of the talk. The central thesis of the talk is that a theoretical understanding of diffraction scattering in gauge theories is in sight and that in this context the phenomenon observed at the CERN collider may correspond to a very particular case. In fact when diffraction scattering experiments at both the CERN and FERMILAB colliders are combined they may provide not only a fundamental verification of QCD, but even determine the quark content of the theory. The talk is organized into three sections

A. A section devoted to reviewing new accelerator results- the latest generation of very detailed diffraction experiments has finally led to the unambiguous conclusion that, in a first approximation, diffraction is produced by a single Regge pole with intercept one-the Pomeron.

B. If indeed diffraction is exactly described as a <u>single interacting</u> Regge pole with intercept <u>exactly</u> <u>one</u> then we have a very special situation in which it follows from analyticity and unitarity alone that all diffractive quantities have logarithmic asymptotic behavior predicted by (Critical Pomeron) Reggeon Field Theory.[1-3] The second section is devoted to presenting these predictions, arguing that they have begun to appear in present energy experiments and in the first collider results[4,5] (the observed KNO scaling is part of the predictions) and that they can be fundamentally confirmed by a full range of experiments at the CERN and FERMILAB colliders.

C. This section is devoted to outlining my theoretical understanding[6-8] of diffraction in gauge theories. That diffraction is described by a single Regge pole already requires the gauge group to be SU(3) while if the intercept is exactly one (Critical Pomeron) then the maximum number of quarks consistent with asymptotic freedom is required.

I would like to emphasize that in my view Regge theory provides an absolutely essential framework for a complete theoretical and experimental understanding of diffraction. Over the years Regge theory has been well demonstrated to be a successful phenomenological description of high-energy experiments. It has also been understood for some time that when extended to multiparticle amplitudes (multi-) Regge theory provides the most powerful theoretical method for analyzing the full implications of unitarity and analyticity at high energy.[9] A very important development from this analysis, which I have only recently discovered[8] and which I shall briefly describe in the following, is that multi-Regge theory provides also a direct means for analyzing the notorious mass-shell infra-red problem of QCD.

A. Recent Accelerator Results

With the last paragraph in mind, the first experimental question, asked many times during the last twenty years, is clearly - can diffraction be described by a single Regge pole, the Pomeron, in first approximation? Remarkably recent experiments at the CERN and FERMILAB accelerators have, at last, given a very clear positive answer to this question. The following five properties can now be regarded as experimentally established for diffraction scattering

A. There is universal shrinkage of diffraction peaks

B. All total cross sections are constants up to logarithms of the total energy-which cause a slow but universal rise

C. Differences of total cross-sections for particles and antiparticles go to zero as a power of the energy.

D. There is factorization of diffractive processes, possibly to within experimental accuracy, and certainly to within 10%

E. Large mass diffractive excitation is non-vanishing at zero momentum transfer.

Properties A - D establish that we can write (in first approximation) for an elastic differential cross-section

$$\frac{d\sigma_{ij}}{dt} \underset{s\to\infty}{\sim} \beta_i^2(t)\,\beta_j^2(t)\; s^{2(\alpha_{\mathbb{P}}(t)-1)} \tag{1}$$

where $\beta_i(t)$ and $\beta_j(t)$ are Regge residue functions and $\alpha_{\mathbb{P}}(t)$ is a single, even signature, Regge trajectory, with intercept

$$\alpha_{\mathbb{P}}(0) = 1 \tag{2}$$

and (experimentally measured) slope

$$\alpha'_{\mathbb{P}}(0) \simeq 0.15\ \mathrm{GeV}^{-1} \tag{3}$$

Property E establishes that the (Reggeon Field Theory) triple Pomeron coupling r_0 is non-zero

r_0 = "  " $\neq 0$

(4)

Although the hypothesis of the Pomeranchuk Regge pole was first advanced[10] twenty years ago, as recently as 1973 it was possible to write[11]

"The forward peak in diffractive elastic scattering .... provided one of the inspirations for the application of Regge theory to strong interactions. It is therefore ironic that today we are in doubt about the relation between diffractive elastic scattering and Regge theory."

A reason for this doubt is easily seen by looking at the then comtemporary plot[12] of elastic slope parameters shown in Fig. 1. If we write

$$\frac{d\sigma_{ij}}{dt} = e^{b_{ij}(t,s)\ t} \tag{5}$$

then clearly (1) implies "universal shrinkage", that is

$$b_{ij} \underset{s\to\infty}{\sim} 2\,\alpha'_{I\!P}(t)\,\ln s \qquad (6)$$

with $\alpha'_{I\!P}(t)$ universal. Fig. 1 can hardly be regarded as evidence for such universal behaviour.

When the same six processes plotted in Fig. 1 are looked at with all recent results added we obtain Fig. 2 (taken from Ref. 13), a strikingly different picture. The solid lines shown are the experimentalists fit to the data and they show that $\alpha'_{I\!P}$ is indeed universal within the accuracy of the fit. (Note that the π-P channels, and possibly K^--P, show the asymptotic shrinkage at the lowest energy. We shall build on this remark later).

A simple picture of elastic slope parameters has finally emerged only as a result of several lengthy experiments carefully separating the t-ranges over which such parameters are measured. It has been found that there is a <u>universal</u> curvature in all slope parameters, of which the "break"[14] in the ISR p-p slope at t ∿ 0.1 GEV is just one manifestation. The existence of this curvature is illustrated in Figs. 3 and 4 which are taken from Ref. 15. At fixed S we can write

$$b_{ij}(t) = b_0^{ij} + c + \cdots \qquad \text{with } C \simeq 5\,\text{GeV}^{-1} \qquad (7)$$

Plotting $b_{ij}(t,s)$ for different values of t, as in Fig. 5. We see that both b_0^{ij} and C must be S-dependent. Equivalently $\alpha'_{\mathbb{P}}$ must be t-dependent so that $\alpha_{\mathbb{P}}(t)$ is certainly not a linear trajectory. In fact the universal curvature C may very well be due to the pion threshold in the trajectory, as originally suggested by Anselm and Gribov.[16]

Although Figs.2 and 5 were plotted before the new ISR $\bar{p}$-p results[17,18] were available we have added then to Fig. 2 and to a small t comparison of p-p and $\bar{p}$-p shown in Fig. 6. Obviously they confirm nicely the general picture.

Property B above is, of course, well-known and well-established. However, just to emphasize the slowness of the rise of total cross-sections[19] we have unconventionally plotted σ_{pp} and $\sigma_{\bar{p}p}$ on a linear rather than a logarithmic energy scale in Fig.7. Also well-known and beautifully confirmed[17,18] at the ISR is property C, that is the power law decrease of all particle/antiparticle cross-section differences. This is shown in Fig. 8, which is taken from Ref. 19. Given that cross-sections rise logarithmically this is a very special situation which is certainly not required on any general theoretical grounds. In fact it is this very special fact which we shall ultimately relate to the underlying gauge group of strong interactions.

Property C establishes that diffraction occurs only in even- signature amplitudes. This leaves the possibility that there is more than one even signature Regge trajectory. However, both the universality of the S-dependence of slope parameters and the factorization property D are consequences of a single trajectory only.

Factorization has now been extensively tested in inclusive large mass diffractive excitation. Multi-Regge theory applied to a one-particle inclusive cross-section gives the triple Pomeron formula

$$M^2 \frac{d^2\sigma_{ij}}{dt\,dM^2} \underset{M^2,\ s/M^2 \to \infty}{\sim} \beta_i(0)\,\beta_j^2(t)\, g_{\mathbb{P}\mathbb{P}\mathbb{P}}(t) \times (M^2)^{\alpha_{\mathbb{P}}(0)-1} \left(\frac{s}{M^2}\right)^{2\alpha_{\mathbb{P}}(t)-2} \tag{8}$$

which when compared with the total cross-section formula

$$\sigma_{ij} \underset{s\to\infty}{\sim} \beta_i(0)\,\beta_j(0)\ s^{\alpha_{\mathbb{P}}(0)-1} \tag{9}$$

gives, as a direct consequence of factorization,

$$M^2 \frac{d^2\sigma_{ij}}{dt\,dM^2} \Big/ \sigma_{ij} \quad \text{is independent of particle } i\,.$$

Experimental results[20] for this ratio are shown in Fig. 9. The M^2 and S independence of (7) implied if $\alpha_{I\!P}(0) = 1$ is now well-established experimentally[20,21] and illustrated in Fig. 10 while the t-dependence of $\alpha_{I\!P}(t)$ is shown in Fig. 11. Clearly

$$g_{I\!P I\!P I\!P}(0) = r_0 \neq 0 \tag{10}$$

is the only possible conclusion from the experimental data.

A further feature of diffractive excitation which will be important in the following is the finite mass sum rule[21] illustrated in Fig. 12. This shows that the triple Pomeron large mass diffractive excitation produces an average of the low mass plus elastic diffractive scattering when extrapolated to low missing mass.

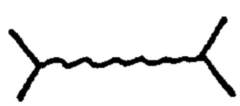
In conclusion I believe that the experimental verification of properties <u>A</u> - <u>E</u> from detailed diffraction experiments carried out over the last five years can not be seriously disputed. It seems unlikely therefore that future experiments will modify the conclusion that, in a first approximation, the Pomeron is a single Regge pole with intercept one. If this is the conclusion of the existing diffraction experiments, a clear objective for the next energy range of experiments is to determine whether this approximate statement is in fact precise. This is what we shall discuss in the next Section. The fundamental significance of such a statement will be the subject of Section C.

B. The Critical Pomeron at $\bar{p}$-p Colliders

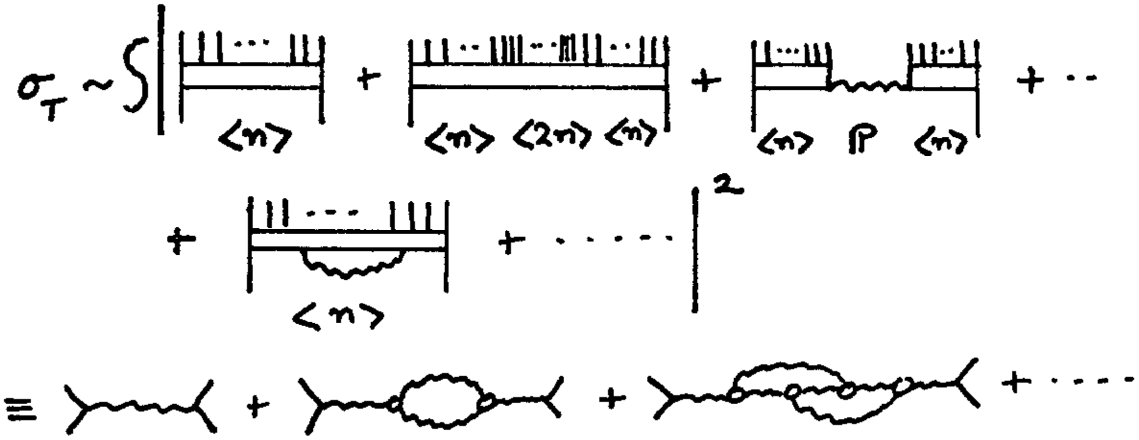
The basis for this section is the following - If the $I\!P$ is a single Regge trajectory with $\alpha_{I\!P}(0)=1$ and $r_0 \neq 0$ it follows from unitarity and analyticity that the precise asymptotic behavior of all diffractive processes can be predicted. Consequently we can hope to convince ourselves that $\alpha_{I\!P}(0)=1$ by looking at a whole range of phenomena and not just by the elusive project of determining the true asymptotic behavior of total cross-sections. First let us very briefly describe the origin of the above statement. It is well-known[22-24] that a single pole can be thought of as originating from some general short-range correlation (in rapidity) production process which, in first approximation, produces the average multiplicity events

$$\langle n \rangle \leftrightarrow \int d\Omega \left| \quad \right|^2$$

$$\rightarrow \quad \equiv s^{\alpha_{I\!P}(t)} \qquad (11)$$



Events with twice the average multiplicity are counted by two Pomeron exchange and so on, while rapidity dependent multiplicity fluctuations are counted by Pomeron interaction graphs. So eventually all fluctuations of multiplicity and absorptive corrections of such fluctuations are counted by a complete set of Reggeon Field Theory graphs. That is



(12)

Graphs of this form represent the dominant processes at asymptotic energies. They can be written as an effective Pomeron field theory[3] with the "Feynman rules"

 $= [E - 1 + \alpha_{\mathbb{P}}(\underline{k}^2)]^{-1}$

 $= r_0$

loop integration $\equiv \int dE\, d^2\underline{k}$

(13)

These rules give the Mellin transform with respect to rapidity ($\int dy e^{Ey}$).It is a consequence of multiparticle t-channel unitarity[8,9,25] that the full set of graphs of an interacting field theory must be present-a very technical use of dispersion theory and multi-Regge theory is needed to prove this.

The task of summing all graphs when $\alpha_{\mathbb{P}}(0)=1$ is analogous to a (statistical mechanics) critical phenomenom problem in the Reggeon Field Theory[1-3] - hence the Critical Pomeron description. It is well known that general scaling properties of such phenomena can be calculated using renormalization group methods. Much work has been done[26] on Critical Pomeron predictions for many diffractive processes. However, much remains to be done and as I shall discuss I believe the $\bar{p}$-p collider results will stimulate much further work on the subject. The central question, which has always been difficult to get any control over,[26] will remain - at what energy scale do the asymptotic predictions become relevant? A-priori this is completely unknown. As suggested[27] many years ago we shall consider it to be open for phenomenological investigation in the following.

In Table 1 we have listed some of the already established scaling (and approach to scaling) predictions of Critical Pomeron behavior. All the scaling functions $F_0, F_1, F_2, \ldots \tilde{F}_0, \ldots$ etc. are in principle precisely calculable. So far only F_0 has been studied in detail. Dash et al.[28] have extended the $O(\varepsilon)$ ($\varepsilon=4-d$ -d=dimension of transverse momentum) calculation of F_0 of Ref. 29 to $O(\varepsilon^2)$. In order to compare their calculation with ISR p-p elastic scattering they parameterized $\beta^4(t)$ (see Table 1) as e^{At} and chose A to maximize the scaling behaviour of the data.

The result with A=0.9 GEV/c is shown in Fig. 13. Clearly Critical Pomeron scaling is approximately satisfied over the whole t-range measured. Having chosen $\beta(t)$ to maximize the scaling the calculated scaling function F_0 can now be inserted in the leading expression for $d\sigma/dt$ given in Table 1. The result is shown in Fig. 14 and is compared with ISR data at the energy where the maximum t-range is available. There is remarkable agreement over the eleven orders of magnitude involved given that we are comparing with experiment an essentially parameter free scaling function calculated (approximately) from first principles. The only effective parameter is the t-scale which has been fixed in Fig. 14 by setting the dip in agreement with the experimental result.

The Critical Pomeron predicts that the same scaling function will eventually appear in all elastic scattering processes. To everyone's surprise it has appeared already[30] in $\bar{p}$-p elastic scattering at P_{lab} = 50 GEV/c as shown in Fig. 15. The appearance of the $\bar{p}$-p diffraction pattern at such a low energy is certainly very encouraging for the hope that collider $\bar{p}$-p energies will be high enough for us to observe a significant number of Critical Pomeron phenomena. However, a similar diffraction pattern has recently been discovered[31] in π-p scattering at 200GEV/c. The qualitative structure is indeed the same but with the difference that the t-scale is a factor of 3 larger! In Fig. 16 we have shown the experimental data and superposed the Critical Pomeron diffraction peak multiplied by the same $\beta^4(t)$ as in p-p but with the t-scale in the scaling function multiplied by a factor of 3. Asymptotically the t-scales should, of course, be the same. Thus while some of the qualitative features of the predicted universal diffraction peaks are emerging at accelerator and ISR energies we are clearly not in true asymptopia. Presumably the π-p dip will move in rapidly to approach that seen in the p-p and $\bar{p}$-p experiments. The Fermilab Tevatron could be very important for checking this.

But will the collider energies be close enough to asymptopia to make sufficient contact with the Critical Pomeron predictions? Moshe and collaborators[32] have begun the task of making usable predictions by exploiting the approach to scaling terms in Table 1. Since F_1 and F_2 have not been calculated theoretically they have used them to fit phenomenologically the discrepancy between the leading term and the experimental results for $d\sigma/dt$ at top FERMILAB and ISR energies. This allows an extrapolation to collider energies. The fit to $d\sigma/dt$ at the top ISR energy is shown in Fig. 17. The resulting prediction for the total cross-section is shown in Fig. 18 while in Figs. 19 and 20 are shown the predictions for the differential cross-section.

In Fig. 21 we have extended the fit of Moshe et al. through the whole energy range covered by the colliders and all Cosmic Ray experiments[33] including the Fly's Eye. Note that while the leading Critical Pomeron term has only a small power of log s the effect of this when combined with the non-leading terms is to give an approximate linear dependence on log s over the whole energy range. While the Cosmic Ray results shown are sometimes regarded with suspicion they certainly do not look bad in terms of the Critical Pomeron prediction. We shall discuss what we mean by the "scaled" Fly's Eye cross-section shortly.

If the colliders are to be close to asymptopia as we would like then the rise of total cross-sections must be significantly slower than the original $[\ln s]^2$ behaviour that was deduced from a dispersion relation analysis[34] including the real part measured at the ISR. Recent experimental results actually support this. First we recall our remark in the previous Section that the behaviour of the π-p slope parameters suggests that this channel may be reaching asymptopia the fastest. The π^-p real part including new measurements[35] is shown in Fig. 22. $\rho_{\pi^- p}$ seems to have stopped increasing and may even be decreasing towards zero as it should do asymptotically. Experimentalists have combined this measurement with the total cross-section results and used a dispersion relation analysis to conclude[35] that the total cross-section should not increase like $[\ln s]^2$ up to collider energies. As Fig. 23 shows the faster the increase at lower energy the sooner the dispersion relation analysis requires a cut-off in the increase.

New ISR measurements[19] of both the p-p total cross-section and ρ pp when combined with Fermilab ρ pp measurements,[15] which disagree significantly with the dispersion relation analysis, suggest a new analysis may produce a modified conclusion about the rise of the p-p total cross-section. ρ pp is shown in Fig. 24 while the comparison of the new ISR results for the total cross-section with the dispersion relation analysis is shown in Fig. 25. Note that the ISR result for the total cross-section at the highest energy has always been outside of the dispersion relation band.

While the total cross-section and the elastic differential cross-section will eventually be measured accurately at both the CERN and FERMILAB colliders it will not be for some time. The initial results concern multiplicities and the rise of the central plateau in rapidity. In fact these quantities have been studied also in terms of the Critical Pomeron although the results have been less widely advertised than the elastic scattering results. The form for the one-particle rapidity distribution given in Table 1 had been previously suggested[36] as an explanation for the logarithmic rise of the central plateau at the ISR. Note that it predicts that only a finite rapidity interval in the central region will rise (like the square of the total cross-section). This is precisely what is seen in the UA5 results[4] shown in Figs. 26 and 27.

As noted in Table 1 all the multiplicity moments have been calculated[37] for the Critical Pomeron-at least the leading term has been calculated. Assuming the next to leading terms are given by the same critical exponents as the differential cross-section we have given a crude extrapolation of the average multiplicity in Fig. 28. The higher multiplicity moments satisfy

$$\langle n^p \rangle \underset{s\to\infty}{\sim} (\ln s)^{p(1+\eta)}$$

$$\sim C_p \langle n \rangle^p \tag{14}$$

which is sufficient to ensure that we have asymptotic KNO scaling. Both the UA1 and UA5 results[4,5] strongly suggest some form of KNO scaling. As Fig. 29 shows, the comparison of the UA1 results with the ISR results[38] suggests that at least the lowest multiplicity moments have changed little from the ISR. To compare the experimental moments with Critical Pomeron predictions we note that the ISR results were plotted in terms of

$$\gamma_2 = \langle (n - \langle n \rangle)^2 \rangle / \langle n \rangle^2 = C_2 - 1 \tag{15}$$

$$\gamma_3 = \langle (n - \langle n \rangle)^3 \rangle / \langle n \rangle^3 = C_3 - 3C_2 + 2 \tag{16}$$

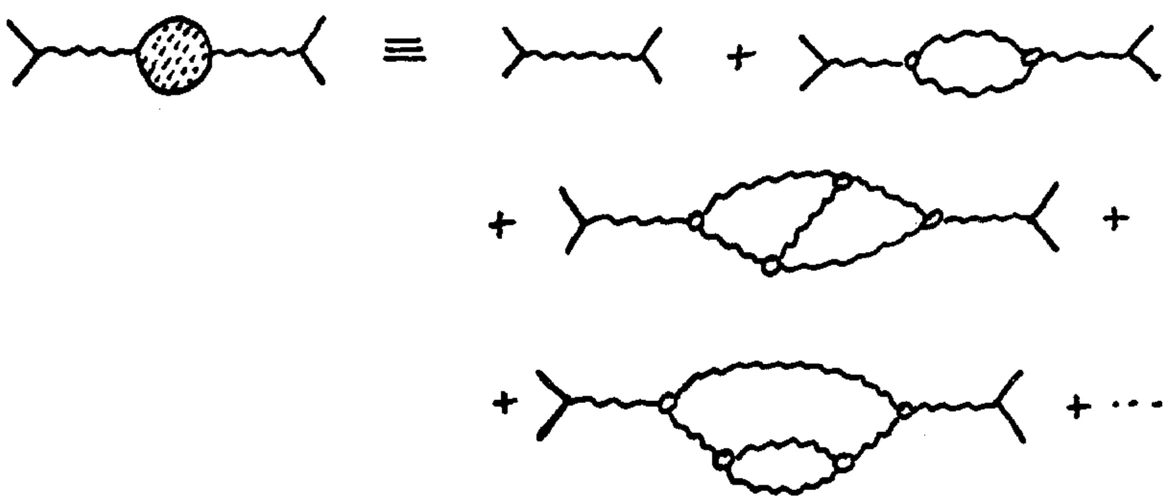
etc. where C_2 and C_3 are defined by (14). They have been calculated[37] only to $O(\varepsilon)$ for the Critical Pomeron. The result is $C_2 = 1.25$ and $C_3 = 1.8$ giving

$$\gamma_2 = 0.25 \qquad \gamma_3 = 0.05 \tag{17}$$

From general experience with non-perturbative evaluations of critical exponents we would certainly expect the exact values of these moments to be significantly higher than (17). This is surely something that will be studied in the near future since from Fig. 30 it looks very reasonable that such values would fit the measured ISR and collider moments very well. In addition, both non-leading terms and the higher moments could also be calculated. In fact the full range of multiplicity moments measured at the colliders could very well provide the strongest evidence for (or against) the Critical Pomeron.

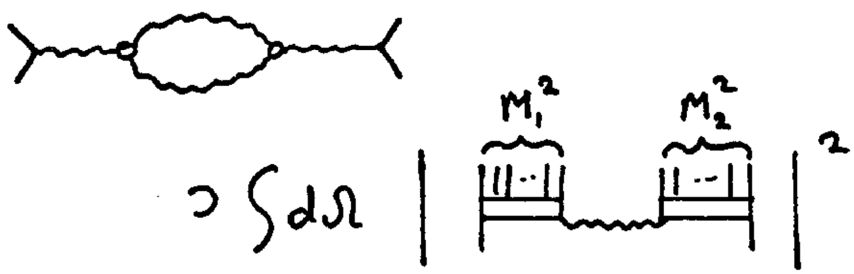
If the total cross-section and elastic differential cross-section measured at the CERN collider match the Critical Pomeron predictions quite well then I would like to advocate performing a detailed triple Pomeron measurement at both the CERN and the FERMILAB colliders. Firstly the well-known $1/M^2$ distribution will acquire logarithmic modifications[29] as shown (to $O(\varepsilon)$) in Fig. 31. More important though the whole diffractive peak in t acquires a predictable M^2 dependence[29] as implied by Table 1 and illustrated in Fig. 32. The elastic-like dip-bump structure moves in and up two-orders of magnitude as M^2 is varied from the lower to upper boundary of the triple Pomeron region. This could serve as a very clear confirmation of Critical Pomeron behavior.

If the Critical Pomeron predictions have begun to appear at present energies and are, even partially, manifest at collider energies then we will, in one sense, have a form of precocious scaling. The earliest estimates[1] of the energy scale needed to see such predictions gave the energy of the universe as the relevant scale. Certainly it is easy[28] to obtain such pessimistically large estimates. The Critical Pomeron predictions come from summing the "Pomeron propagator" graphs



(18)

Our discussion in the previous Section implies that we need a rapidity of at least four or five ($\ln s \simeq 4,5$) to isolate the simple Pomeron from background behavior. One would then expect a similar rapidity interval to be needed to isolate each Pomeron in the higher-order graphs. This would give a rapidity of twelve for the second graph and a rapidity of twenty for the third etc. For the sum of the series to become relevant we might expect a rapidity interval of anything from thirty to several hundred to be required. Since we have twelve at the CERN collider and sixteen at the FERMILAB collider the situation can easily be argued to be hopeless. It is at this point that the finite mass sum rule[21] illustrated in Fig. 12 plays a central role. This implies that the second graph in (18) not only counts double high mass diffractive excitation (for which a rapidity interval of twelve might very well be required)

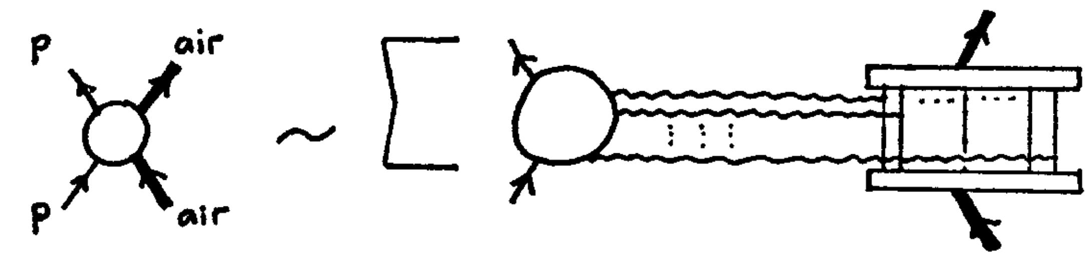


$$M_1^2, M_2^2 \gg 1 \qquad (19)$$

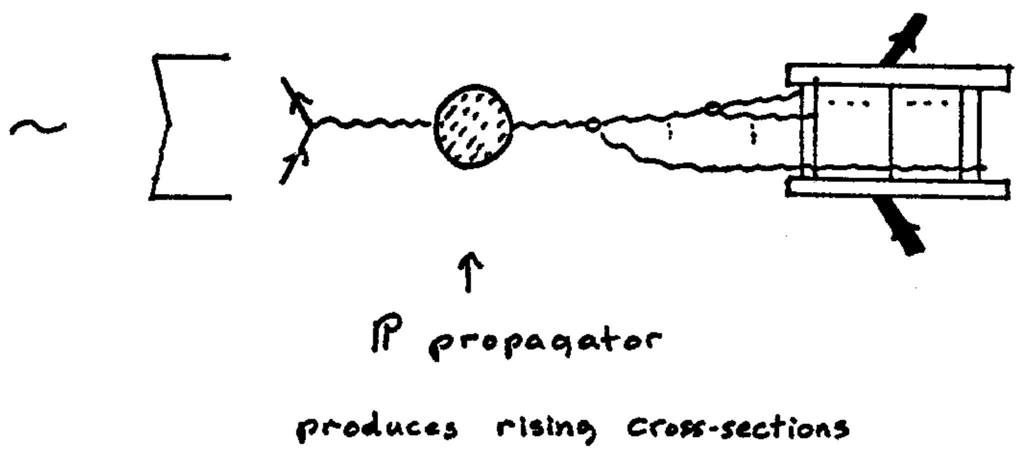
but because of the extrapolation shown in Fig. 12 also well reproduces (in average) events where either M_1^2 or M_2^2 or both are not at all large. Hence this graph makes its appearance at a much lower rapidity than might be expected. If this situation generalizes then the asymptotic results can very well appear at a much lower rapidity than the pessimistic estimates would give.

If this is the case then the rise of total cross-sections can be thought of as due entirely to diffractive excitation (and associated processes) producing the Pomeron propagator graphs of (18). The rise therefore involves a factorizing coefficient multiplying a logarithmically rising factor which is independent of the scattering particles. This form of dynamics is quite orthogonal to that of models which consider multiple rescattering as a dominant feature. In particular it implies that attempts[39] to use a Glauber-type model to compare the rise of the p-p cross-section with that of the p-air cross-section measured in Cosmic Ray events will be misleading. Many people[40,41] have previously argued that the Glauber formalism is not adequate for high-energy nucleus scattering because of diffractive excitation. However, we are going even further in advocating that diffractive excitation (and directly associated processes) be thought of as the dominant mechanism producing <u>all</u> rising cross-sections -- including the p-air cross-section.

Applying the finite mass sum rule (generalized) extensively we can qualitatively describe proton-air scattering as follows



(20)



(21)

Hence the rising cross-section for proton-air scattering has the same origin as that of proton-proton scattering and will simply be multiplied by a different overall constant.

Therefore if the p-air cross-section at 10^9 GeV is around 540 mb., as the preliminary Fly's Eye result announced at this meeting[42] suggests, then since it rises from around 280m.b. at 10^3 GeV we expect the p-p cross-section to rise to a 10^9 GeV value given by

$$42 \times \frac{540}{280} = 81 \text{ m.b.} \tag{22}$$

This is the "scaled" Fly's Eye cross-section appearing on Fig. 21. It will not escape the readers attention that it lies right on the Critical Pomeron prediction. If (22) seems absurdly simple let us note that, within experimental accuracy, the p-p and p-air cross-sections do rise in proportion over the energy range where both rising cross-sections have been explicitly measured. In addition the relation between pp and p-air used[33] to extract the cosmic ray results up to 10^5 GeV (shown in Fig. 21) is linear, as shown in Fig. 33. Therefore I believe it makes little sense to use Glauber theory to justify the use of a non-linear relation between 10^5 GeV and 10^9 GeV.

In conclusion then all evidence suggests that at the colliders we will see all the logarithmic effects typical of the asymptotic behavior produced by a single interacting Regge pole with intercept exactly one. Certainly nothing suggests that logarithmically increasing quantities will halt their increase. Therefore if all asymptotic behavior persists as predicted from the CERN to the FERMILAB $\bar{p}$-p collider what will have been learned? I hope the next Section will provide a sufficiently interesting answer to justify any of the relevant experiments.

C. Diffraction in Gauge Theories

Calculating high-energy behavior of gauge theories is, of course, very complicated. To get the right answers we expect to have to face the fundamental dynamical problems of confinement and chiral symmetry breaking (and we do have to!). I shall first list the results[6-8] that I see emerging for the dependence of diffraction on both the gauge group and the quark content of the theory. I shall then briefly describe the method used to derive the results. Finally I shall discuss their physical origin and significance.

Emerging Results

SU(2) Gauge Theory

There is no rising cross-section for any number of fermions. (The number of fermions is always restricted by asymptotic freedom in my work. The necessity for this can be seen directly from Regge limit calculations[6] or simply taken as a pre-requisite for a finite short-distance theory.) So

$$\sigma_T \to 0 \qquad \forall \; N_F$$

SU(3) gauge theory

$$\sigma_T \to 0$$

except

$$\left.\begin{array}{l}\text{a) 16 flavours of triplet quarks} \\ \text{or} \\ \text{b) 6 flavours of triplet quarks} \\ \quad + \text{2 flavours of sextet quarks}\end{array}\right\} \to \begin{array}{l}\text{Reggeon Field Theory} \\ \text{Critical Pomeron}\end{array}$$

$$\Rightarrow \quad \sigma_T \to \infty \, , \quad \left[\frac{d\sigma}{dt}\right]_{\bar{p}p} - \left[\frac{d\sigma}{dt}\right]_{pp} \to 0$$

There is factorization and all the predictions of the Critical Pomeron discussed in the previous Section.

SU(4) Gauge Theory

$$\sigma_T \to 0 \qquad N_F < 20$$

$N_F = 21 \quad \sigma_T \to \infty$ but there is also an odd-signature Pomeron trajectory and so

$\left[\frac{d\sigma}{dt}\right]_{\bar{p}p} - \left[\frac{d\sigma}{dt}\right]_{pp} \not\to 0$ and (probably) there is no factorization

SU(N) Gauge Theory

The number of Pomeron Regge trajectories of both signatures increases with N. Close to the maximum number of fermions allowed by asymptotic freedom is needed to obtain a rising cross-section. In general if $\sigma_T \to \infty$ then

$$\left[\frac{d\sigma}{dt}\right]_{\bar{p}p} - \left[\frac{d\sigma}{dt}\right]_{pp} \not\to 0$$

and there is no factorization.

From these results we obtain the striking conclusion that QCD (SU(3) gauge group) saturated with quarks (the asymptotic freedom constraint is only just satisfied by either a) or b) above) is the (almost) unique theory giving

1. rising cross-sections
2. $\left[\frac{d\sigma}{dt}\right]_{\bar{p}p} - \left[\frac{d\sigma}{dt}\right]_{pp} \to 0$

3. the Pomeron is a single Regge pole giving factorization and all the asymptotic predictions of the Critical Pomeron.

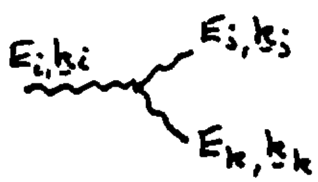
Clearly these are strong results which go a long way beyond any understanding of diffraction in gauge theories claimed by other authors. The technical tool used for their derivation is multi-Regge theory.[6,9] In effect this allows us to use analyticity and unitarity to control infinite sums of infra-red divergent perturbation theory diagrams.

We begin with SU(N) gauge theory containing massive quarks and (N-1) fundamental representations of Higgs scalars -- this avoids[43,44] a phase-transition when we use the Higgs mechanism to give all gluons masses. In this case both quarks and gluons are physical particles and most important[45-49] they lie on Regge trajectories which can be exchanged at high energy. Scattering amplitudes are given by reggeon diagrams[6,50,51] which now involve gluons and quarks instead of Pomerons e.g.

(23)

where

$$= \text{gluon propagator} = \frac{1}{E-\Delta(\underline{k}^2)} \times \frac{1}{\underline{k}^2 - M^2} \tag{24}$$



$$= g\, f_{ijk} \left[E_i - \Delta(\underline{k}_j^2) - \Delta(\underline{k}_k^2) \right] \tag{25}$$

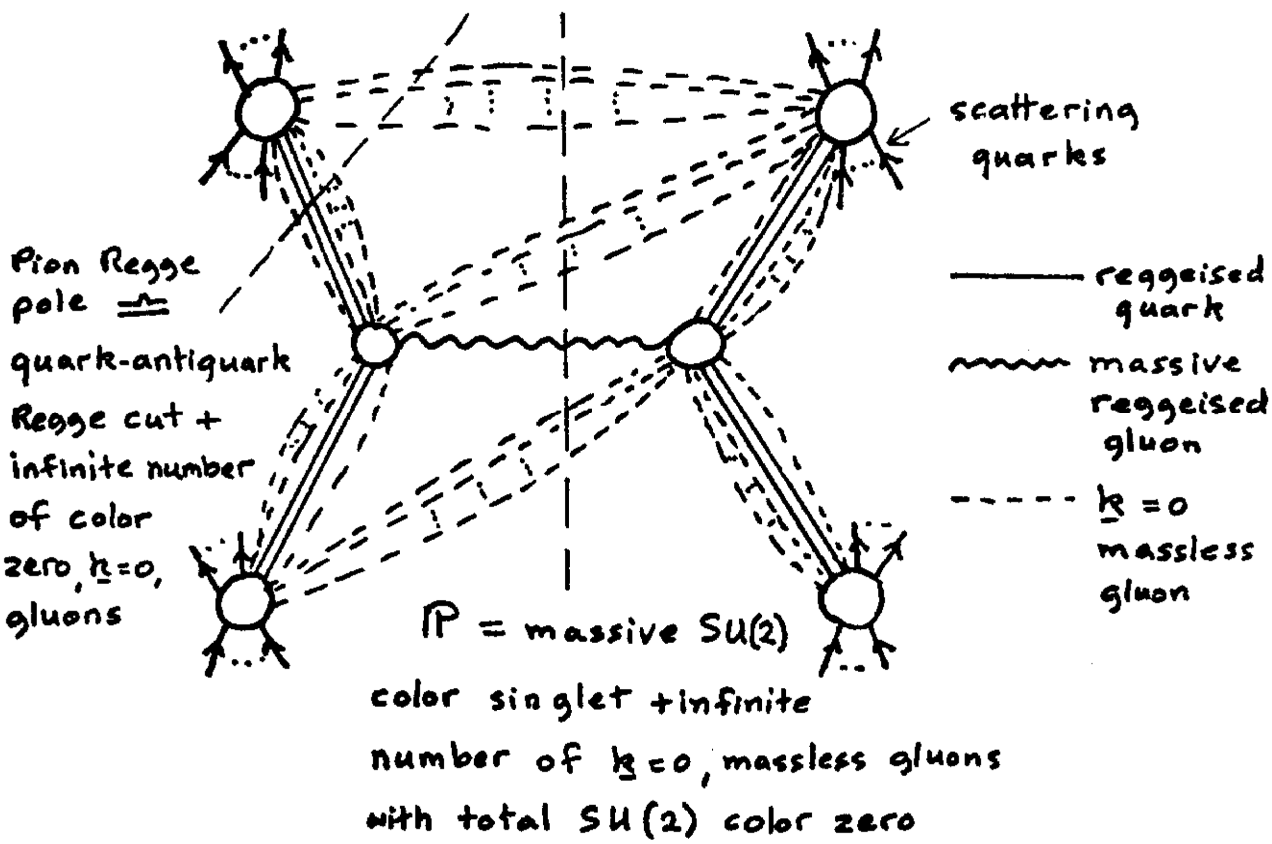
$$\Delta(\underline{k}^2) = \frac{g^2}{16\pi^2} (\underline{k}^2 - M^2) \int \frac{d^2 q}{(q^2 - M^2)((\underline{k}-q)^2 - M^2)} \tag{26}$$

g is the coupling constant, f_{ijk} are the group structure constants. The pole in k^2 in (24) and the "nonsense-zero" [ ] in (25) result from the odd signature of the reggeized gluon trajectory. These factors also prevent the writing of simple field theory rules for diagrams with interactions. [Strictly[6] we have to compute imaginary parts and use quite complicated cutting rules to calculate even the simplest loop diagram in (23)]. Nevertheless the reggeon diagram rules for quarks and gluons are the simplest possible consistent with multi-Regge theory -- this has been checked up to tenth order in perturbation theory.[6,48-51]. Consequently the full power of multiparticle dispersion theory[52,53] combined with multi-Regge theory[6,9] can be used to construct a complete set of reggeon diagrams to describe the high-energy behavior of arbitrary scattering amplitudes.

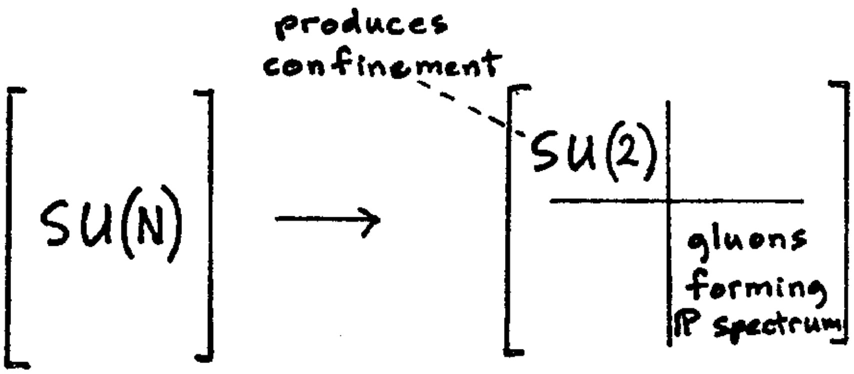
To calculate real QCD, and an unbroken gauge theory in general, we must remove the gluon masses. Since we are calculating S-Matrix elements this is the well-known infra-red problem of QCD. Fortunately there is an <u>exponentiation of infra-red divergences</u> which is just "reggeization" of the gluons, that is

$$s^{\alpha(t)} = e^{\ln s\,\alpha(t)} \underset{M^2 \to 0}{\sim} e^{-\ln s \ln t/M^2} \tag{27}$$

If we first restore the gauge-symmetry to SU(2) by removing one Higgs representation we can analyze this exponentiation using multi-Regge theory for interacting reggeons (that is reggeon unitarity etc.). This is my claim that infinite sums of divergent diagrams can be controlled by unitarity and analyticity. The infra-red analysis is complicated[8] and in fact forces us to S-Matrix elements, for multi-quark scattering, which contain bound-state scattering amplitudes. These bound-state amplitudes are infinite relative to the quark amplitudes and this is how the confinement emerges. That is color-zero hadrons are picked out by a special class of infra-red singularities that do not exponentiate but can be factorized on to external states. For example, a pion scattering amplitude containing a single Pomeron exchange emerges from reggeon diagram amplitudes of the form



SU(2)Color zero, k=0 massless gluons form a vector state with color charge parity +1. They behave as a vacuum background producing confinement with chiral symmetry breaking. They produce hadrons by combining with color-zero combinations of quarks and the Pomeron by combining with color-zero massive gluons. Consequently the spectrum of Pomeron trajectories is determined by that part of the gauge group orthogonal to an SU(2) subgroup (when all but this subgroup is broken by the Higgs mechanism). That is



This is enough to see that

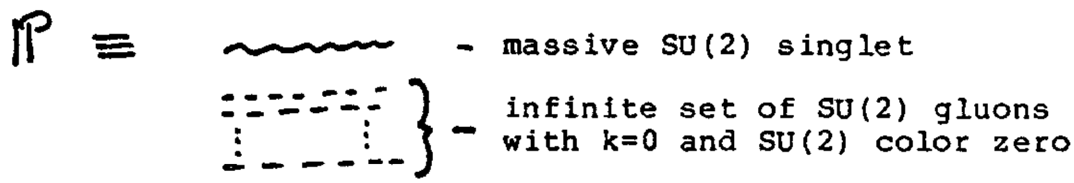
i) there is no $\mathbb{P}$ in SU(2) (with $\alpha_{\mathbb{P}}(0)\sim 1$)

ii) SU(3) has a single $\mathbb{P}$ trajectory

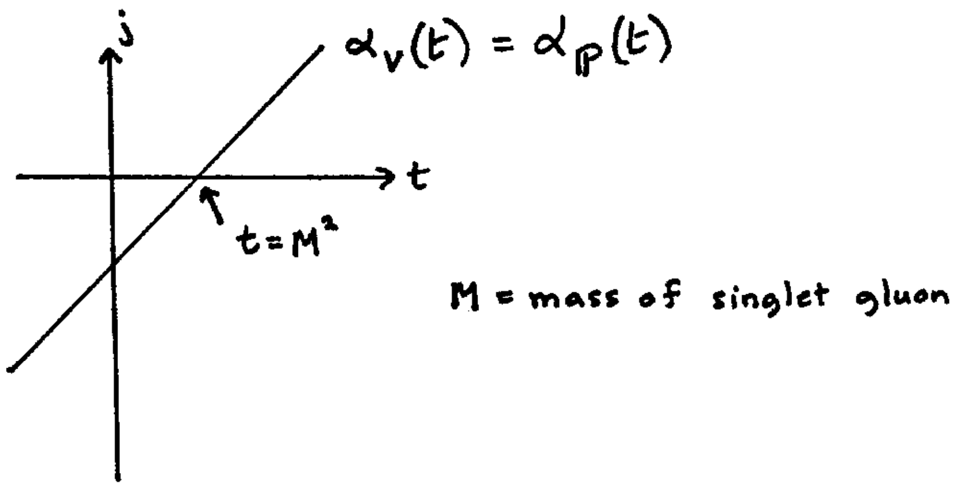
iii) SU(4) has a more complicated $\mathbb{P}$ spectrum

We shall not give more details of the analysis here but finally describe how we control the Pomeron intercept in QCD.

From the above if we consider QCD with one triplet of Higgs scalars used to break the gauge symmetry to SU(2) then the Pomeron is, in first aproximation



This implies the Pomeron Regge trajectory is exchange degenerate with the odd-signature trajectory on which the massive singlet lies



Therefore it seems that $\alpha_{\mathbb{P}}(0) \to 1$ when $M^2 \to 0$, which suggests that

$$\text{SU(2) gauge symmetry} \to \text{SU(3)}$$
$$\Rightarrow \alpha_{\mathbb{P}}(0) \to 1$$

(In fact a detailed Reggeon Field Theory analysis using the "Supercritical Pomeron"[54] is required to show that the odd-signature gluon trajectory simultaneously decouples from physical states). This argument works in detail only if the singlet gluon mass M^2 is an unambiguous S-Matrix mass independent of any cut-off parameter. This is the case only if the QCD plus Higgs scalars theory, from which we start, is asymptotically free. This condition requires[55,56] that we have the maximum number of quarks consistent with the asymptotic freedom of the pure SU(3) gauge theory. Alternatively if we have fewer quarks, then keeping a transverse momentum cut-off in the theory until after the SU(3) symmetry is restored, we can show[6] that the Pomeron intercept is less than one. We therefore arrive at the results described above.

That the Pomeron should depend on the gauge group is at first surprising but in fact rather natural if we consider a string-like confining solution of the gauge theory in which the strings reflect the properties of line-integrals of electric flux, as expected. In this case the Pomeron should be given, in first approximation, by the exchange in two transverse dimensions of a closed string. Since such closed strings should reflect the properties of Wilson loops in two spacelike dimensions the following properties[57] naturally match the properties of the Pomeron listed above. Defining

$$\phi(\circlearrowleft) = \mathrm{Tr}\ P \exp\left[\oint_{\circlearrowleft} A(x).dx \right.$$

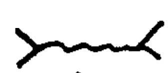
1. ϕ is real in SU(2) $\equiv$ no imaginary $\mathbb{P}$ in SU(2)

2. ϕ is orientation dependent in SU(3) with $\phi(\circlearrowright) - \phi(\circlearrowleft)$ imaginary and even under rotation through 2π $\equiv$ one even signature $\mathbb{P}$ trajectory in SU(3)

3. In SU(4), $\phi(\circledcirc)$ is real, distinct from the product of two simple loops and no longer even under rotation through 2π $\equiv$ there is an additional odd signature $\mathbb{P}$ trajectory in SU(4).

4. In SU(N) the increasing complexity of spacelike Wilson loops matches the increasing complexity of the $\mathbb{P}$ spectrum.

I believe a more detailed discussion of both my infra-red analysis and the above properties of Wilson loops would make the above correspondence much more concrete but I shall not attempt it here. Note that the Pomeron phenomenology which begins Section 2 would when applied to the string model give the following

$\langle n \rangle$ → simple closed string exchange → 

$2\langle n \rangle$ → exchange of two simple closed strings → 

(+, in SU(4), double loop in 3) above) (+ additional $\mathbb{P}$ trajectory)

Consequently the additional odd-signature trajectory in SU(4) will manifest itself in events with twice the average multiplicity. Similarly in SU(N), events with up to (N-2) times the average multiplicity will manifest new Regge trajectories. Therefore it is very attractive that if the very high multiplicity fluctuations observed at collider energies are really described by a single Regge pole theory then we have determined the strong interaction gauge group to be SU(3).

Finally if the intercept of the Pomeron is exactly one in that all logarithmic increases persist and appear to be a true asymptotic phenomenom, what is the implication? I believe that this should be interpreted as evidence that QCD is saturated with quarks. There are plausible arguments for this outside of strong-interaction high-energy behavior.

a) There are arguments[58] that chiral theories are inconsistent at high-energy so that above the weak interaction scale all existing flavours of quarks will be doubled. That is the $SU(2)_L$ of Weinberg-Salam must go to at least $SU(2)_L \times SU(2)_R$. If there are four conventional families, that is eight flavours, below the weak-interaction scale, we expect eight families or sixteen flavours eventually. A very reasonable possibility.

b) More attractive perhaps is the possibility that there is an $SU(2)_L$ family of sextet quarks. They could naturally provide[59] the condensate giving masses to the weak interaction vector bosons. The lagrangian masses of such quarks could be essentially zero while they would produce no hadrons (sextet pions) with this mass scale. Thus, given the existence of the top quark, QCD would be saturated with quarks at a scale well below where we see the asymptotic phenomena. (This would not be the case for option a) above, which is therefore less satisfactory.) There are even arguments[60] that the magnitude of the gauge coupling could be be fixed at approximately the right experimental value in an appropriate grand unified theory. Saturating QCD with six flavours of triplet quarks and two flavours of sextet quarks therefore provides a very economical description of many aspects of physics requiring no technicolor or hypercolor gauge groups and possibly explaining the observation of Critical Pomeron scaling at the CERN and FERMILAB colliders!

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TABLE 1

Critical Pomeron Scaling and Approach to Scaling Predictions

$\frac{d\sigma}{dt}$	$\beta^4(t)\ (\log s)^{2\eta}\ F_0^2\left[ct\ (\log s)^z\right] \Big\{1 + 2F_1\left[ct\ (\log s)^z\right]\ (\log s)^{-\lambda} - 2F_2\left[t,ct\ (\log s)^z\right]\ (\log s)^{-\eta-1} + \ldots\Big\}$
σ_{tot}	$\beta^2(0)\ (\log s)^\eta\ \left[1 + F_1(0)\ (\log s)^{-\lambda} - F_2(0)\ (\log s)^{-1-\eta} + \ldots\right]$
$M^2\ \frac{d\sigma}{dM^2dt}$	a)*) At $\log M^2 \ll \log (s/M^2)$: $\beta^2(t)\beta(0)\ \frac{\left[\log (s/M^2)\right]^{\alpha_1}}{\left[\log M^2\right]^{\alpha_2}}\ F_0^2\left[ct\ (\log M^2)^z\right] \Big\{1 + N_1(\log M^2)^{-\lambda} - N_2(\log M^2)^{-1-\eta} + F_3\left[ct\ (\log (s/M^2))^z\right]\left[\log (s/M^2)\right]^{-\lambda} + F_4\left[ct\ (\log (s/M^2))^z\right]\left[\log (s/M^2)\right]^{-1-\eta} + \ldots\Big\}$ b)**) At $\log M^2 \gg \log (s/M^2)$: $\beta^2(t)\beta(0)\ \frac{\left[\log (s/M^2)\right]^{\alpha_3}}{\left[\log M^2\right]^{\alpha_4}}\ \tilde{F}_0\left[ct\ (\log (s/M^2))^z\right] \Big\{1 + \tilde{N}_1(\log M^2)^{-\lambda} - \tilde{N}_2(\log M^2)^{-1-\eta} + \tilde{F}_3\left[ct\ (\log (s/M^2))^z\right]\left[\log (s/M^2)\right]^{-\lambda} + \tilde{F}_4\left[ct\ (\log (s/M^2))^z\right]\left[\log (s/M^2)\right]^{-1-\eta} + \ldots\Big\}$
$\frac{d\sigma}{dy}$	$N\left(\frac{Y}{2} - y\right)^\eta\left(\frac{Y}{2} + y\right)^\eta \Big\{1 + N_3\Big[\left(\frac{Y}{2} - y\right)^{-\lambda} + \left(\frac{Y}{2} + y\right)^{-\lambda}\Big] + N_4\Big[\left(\frac{Y}{2} - y\right)^{-1-\eta} + \left(\frac{Y}{2} + y\right)^{-1-\eta}\Big] + \ldots\Big\}$

*) $\alpha_1 = 2\eta,\ \alpha_2 = 1 + \frac{1}{2}\eta - \frac{D}{4}z$.

**) $\alpha_3 = -1 + \frac{1}{2}\eta + \frac{D}{4}z,\ \alpha_4 = -\eta$.

Critical exponents: $\eta = 0.26 \pm 0.02,\ z = 1 + \zeta = 1.13 \pm 0.01,\ \lambda = 0.49 \pm 0.01$. $(D = 2)$.

Multiplicity moments

$$\langle n^p\rangle = C_p[\ln s]^{p\eta} + \cdots$$

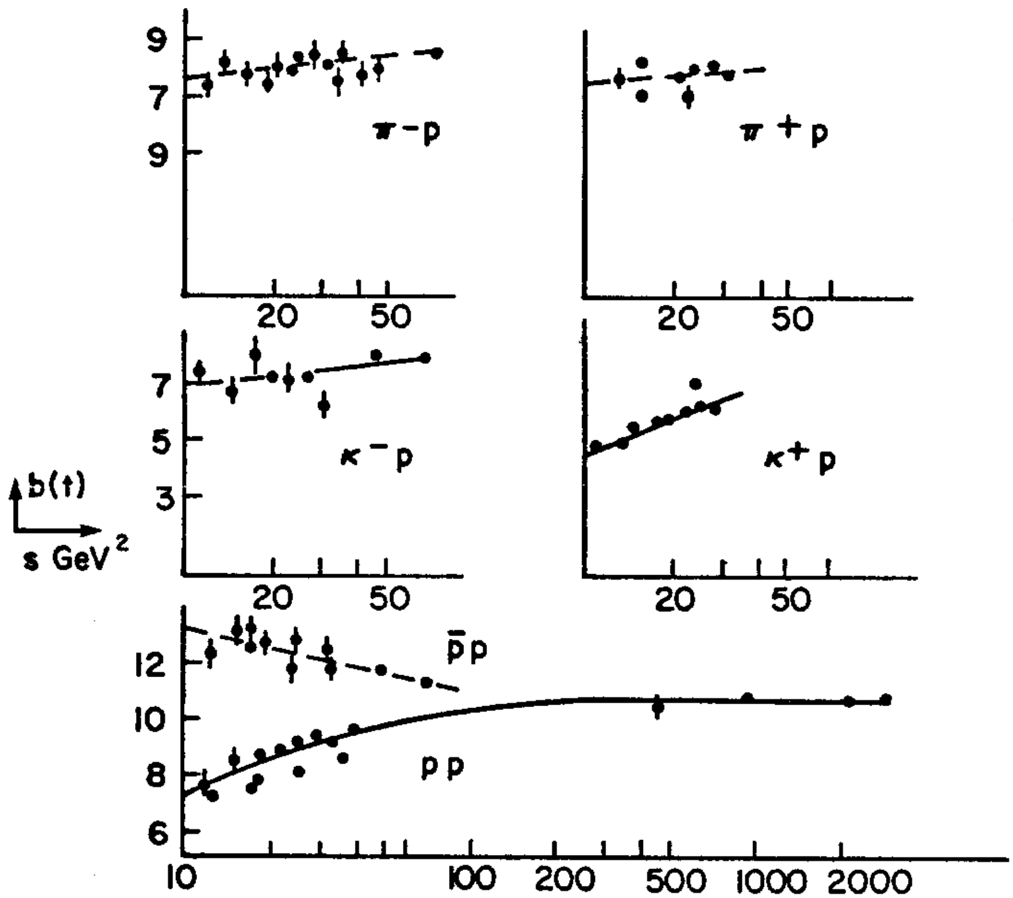

Fig. 1. Slope parameters as measured up to 1973.

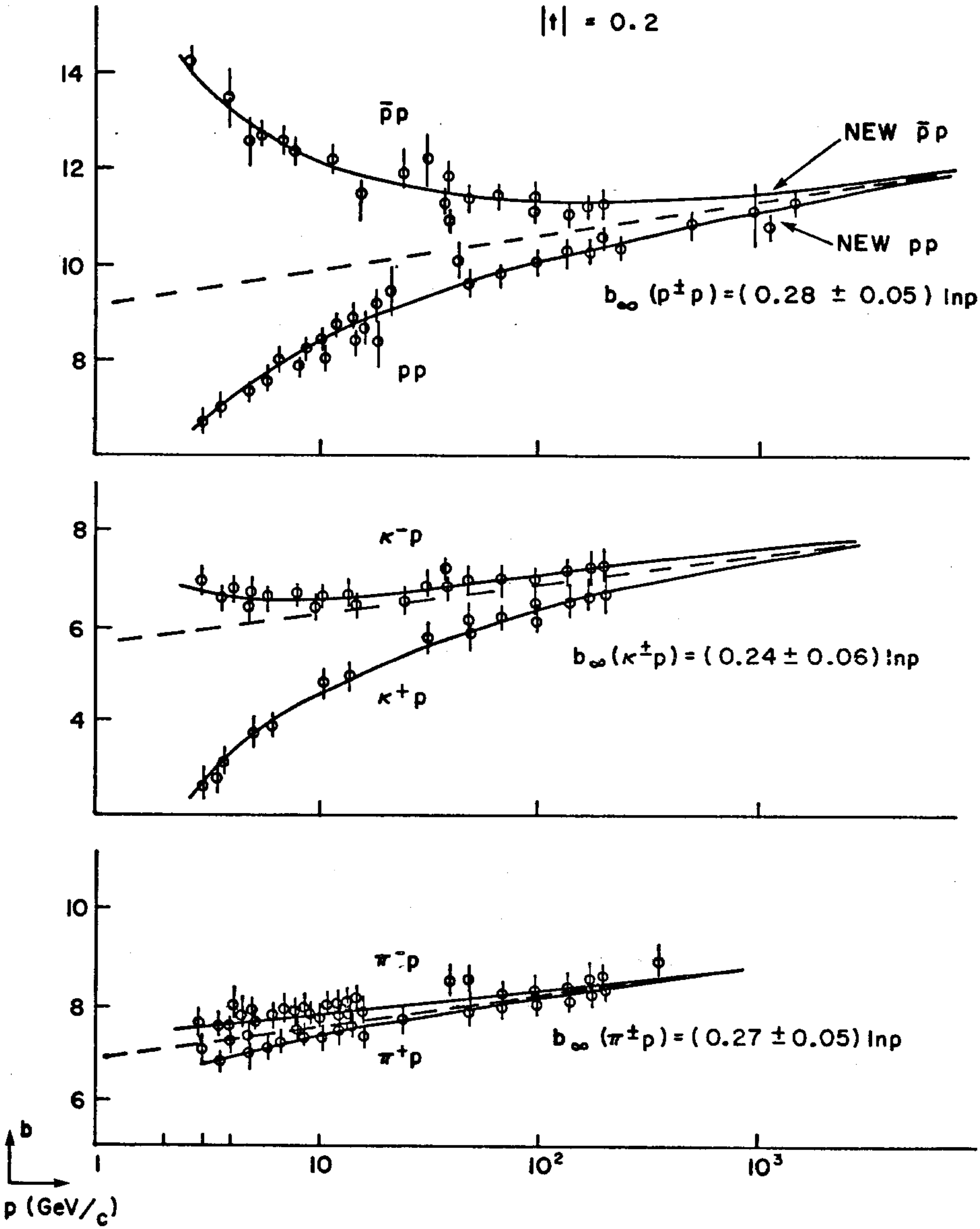

Fig. 2. Present-day compilation of slope parameters.

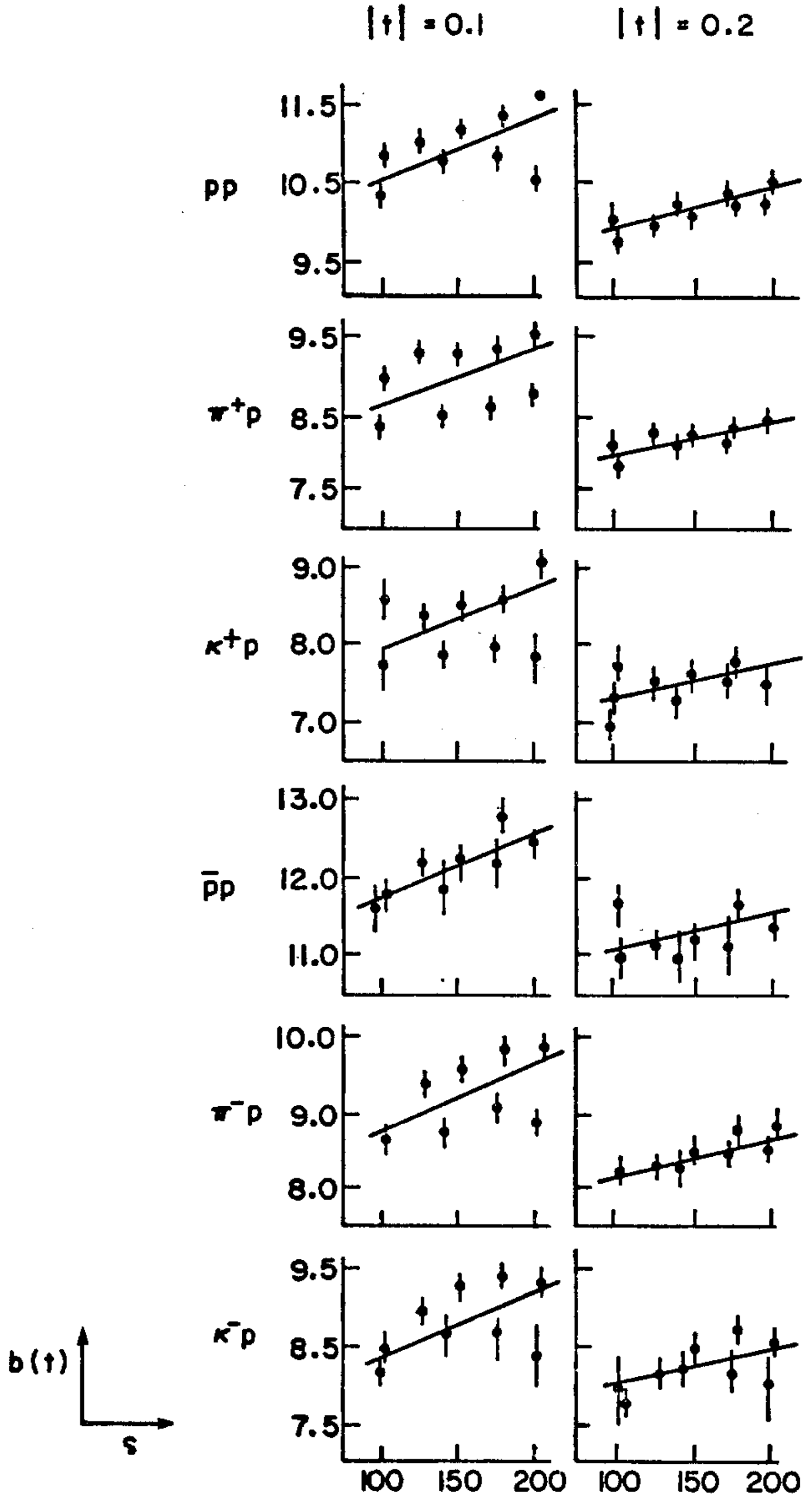

Fig. 3. t-dependence of b(t,s). The solid lines are to guide the eye and are not fits. The universal curvature is manifest even in the narrow t-range shown.

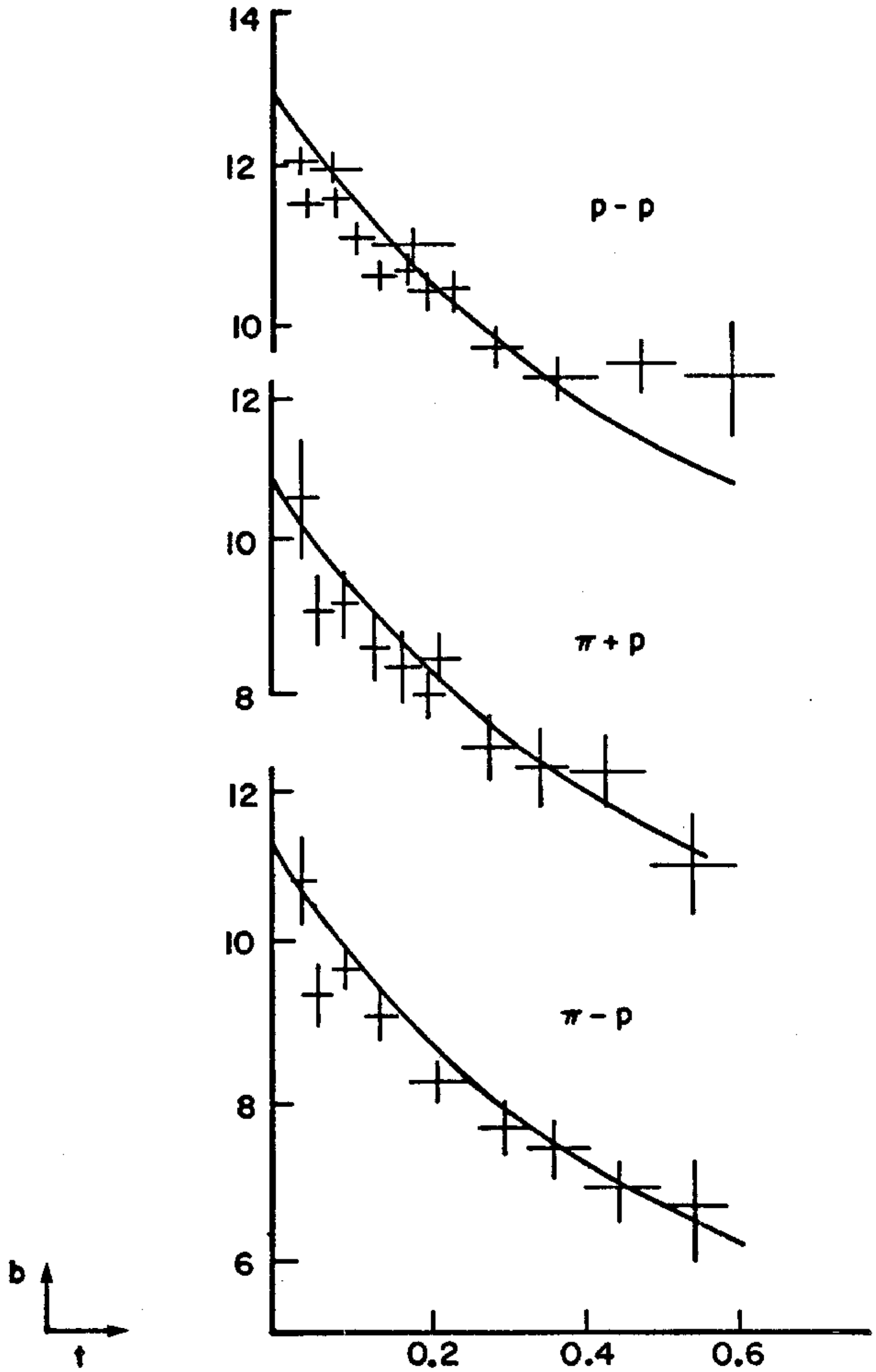

Fig. 4. Universal curvature over the whole t-range.

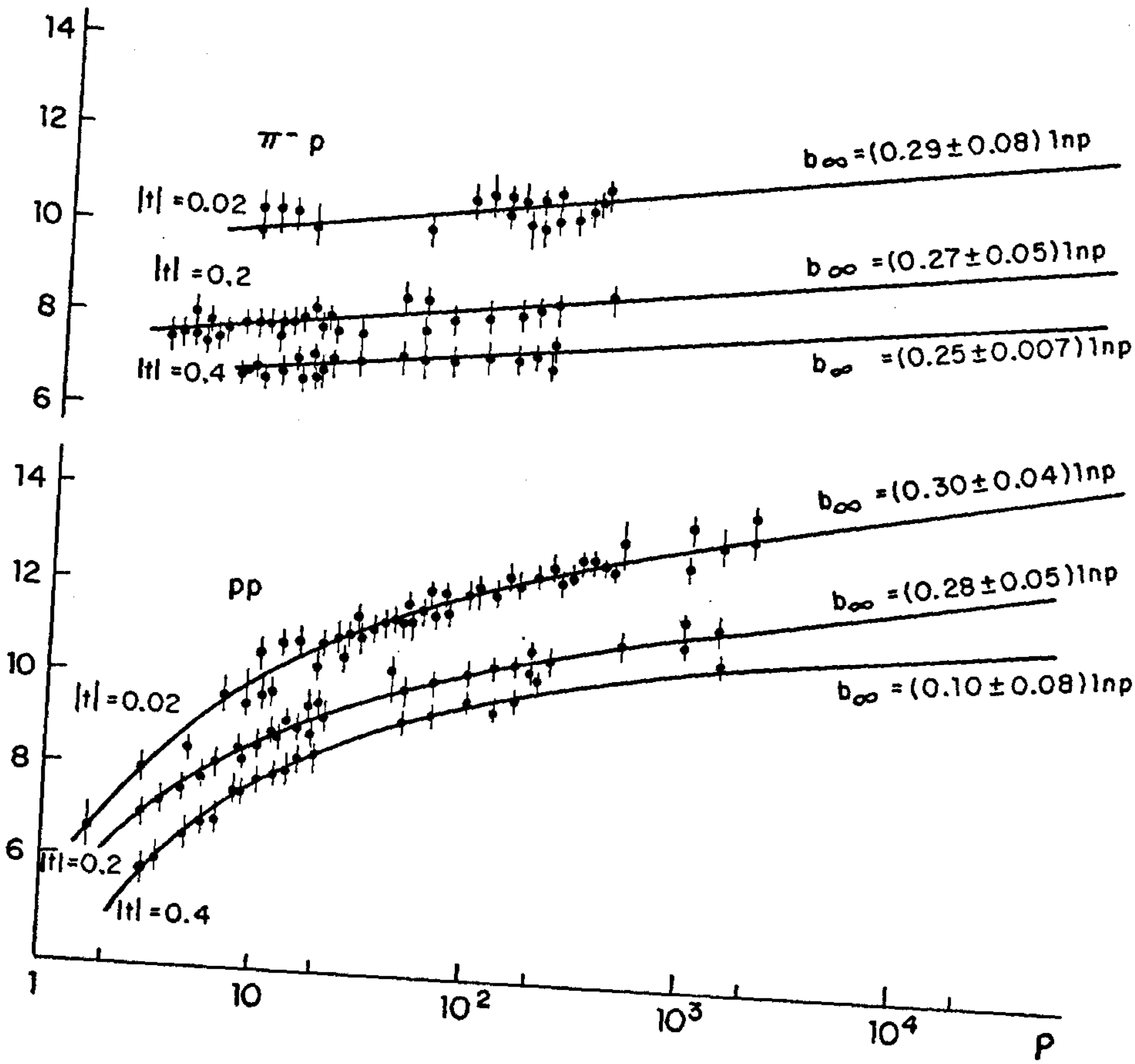

Fig. 5. b(t,s) for $\pi^- p$ and pp illustrating that α_P' is universal but with some t-dependence.

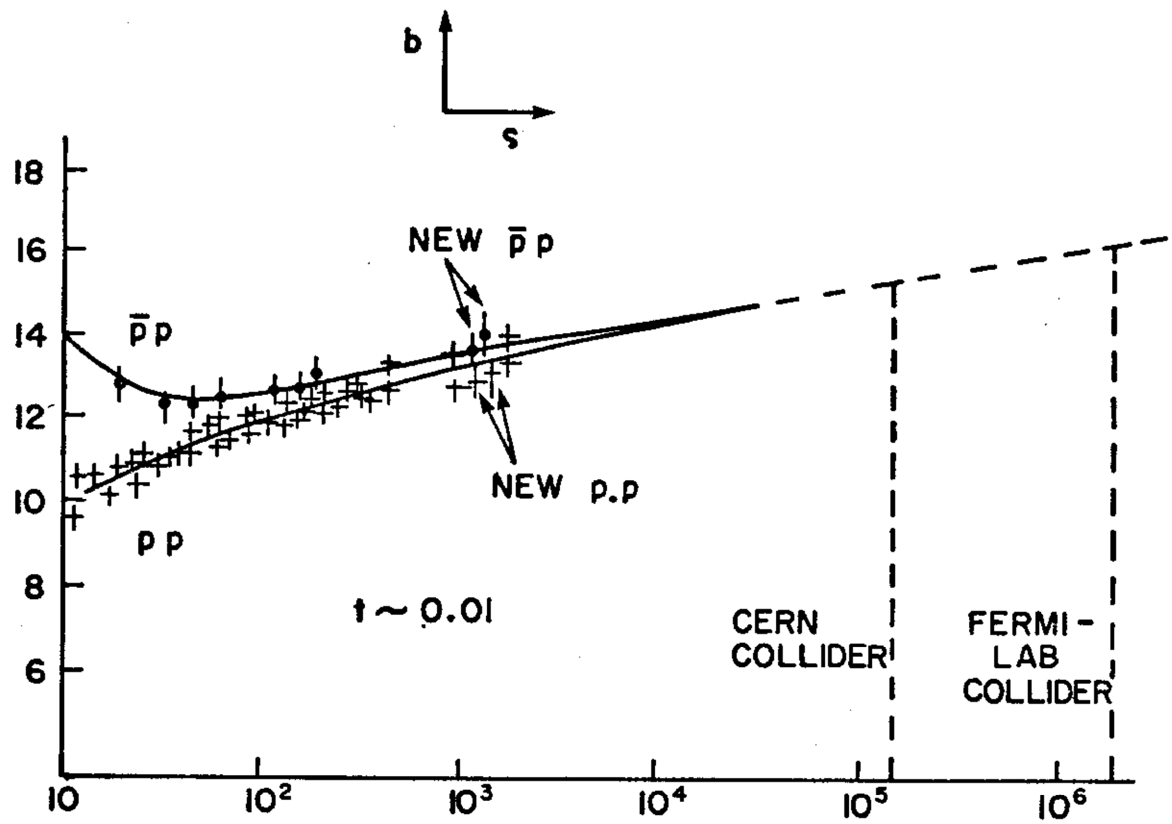

Fig. 6. The p-p and $\bar{p}$-p slope parameters extrapolated to collider energies.

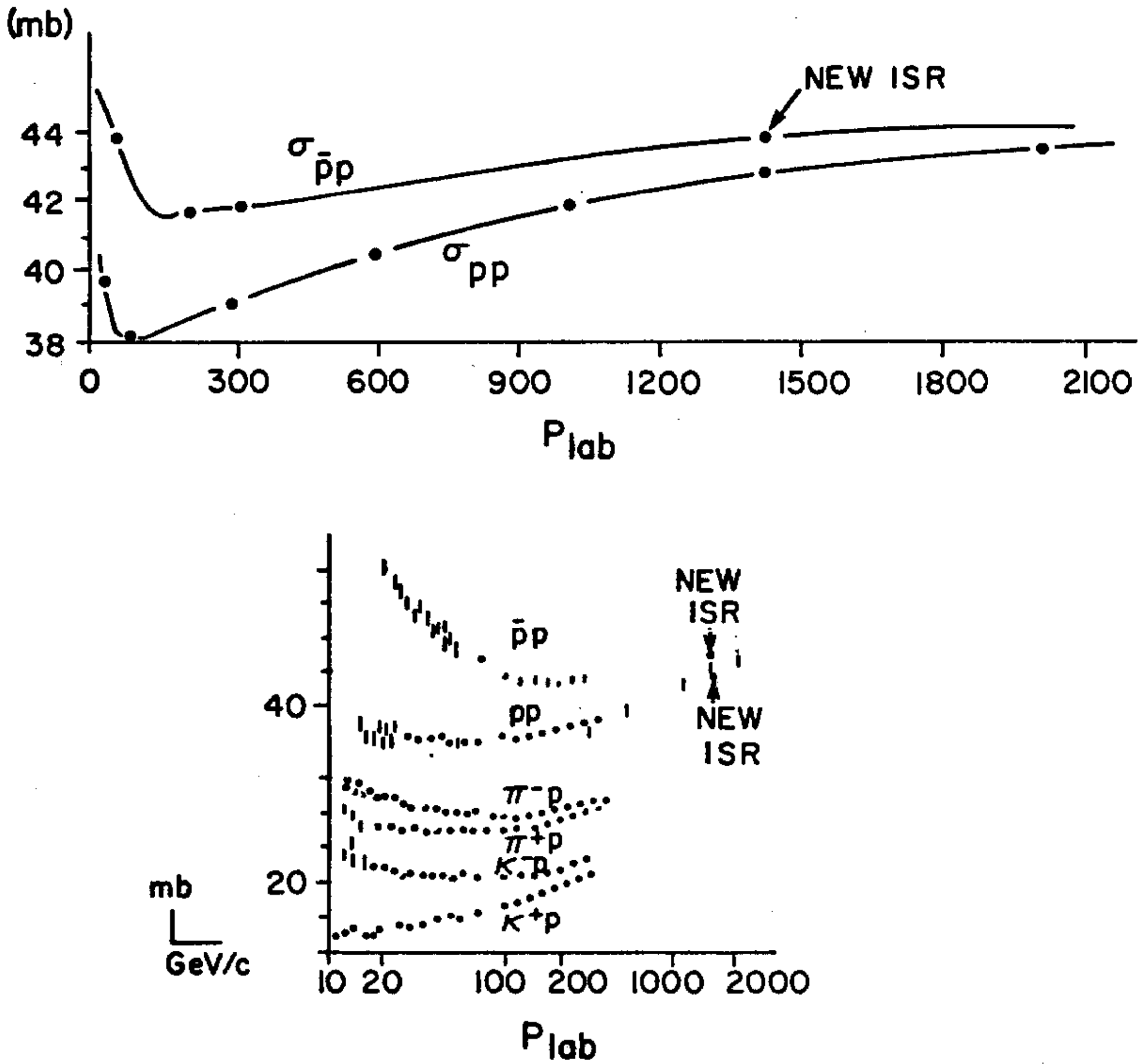

Fig. 7. The logarithmic rise of total cross-sections.

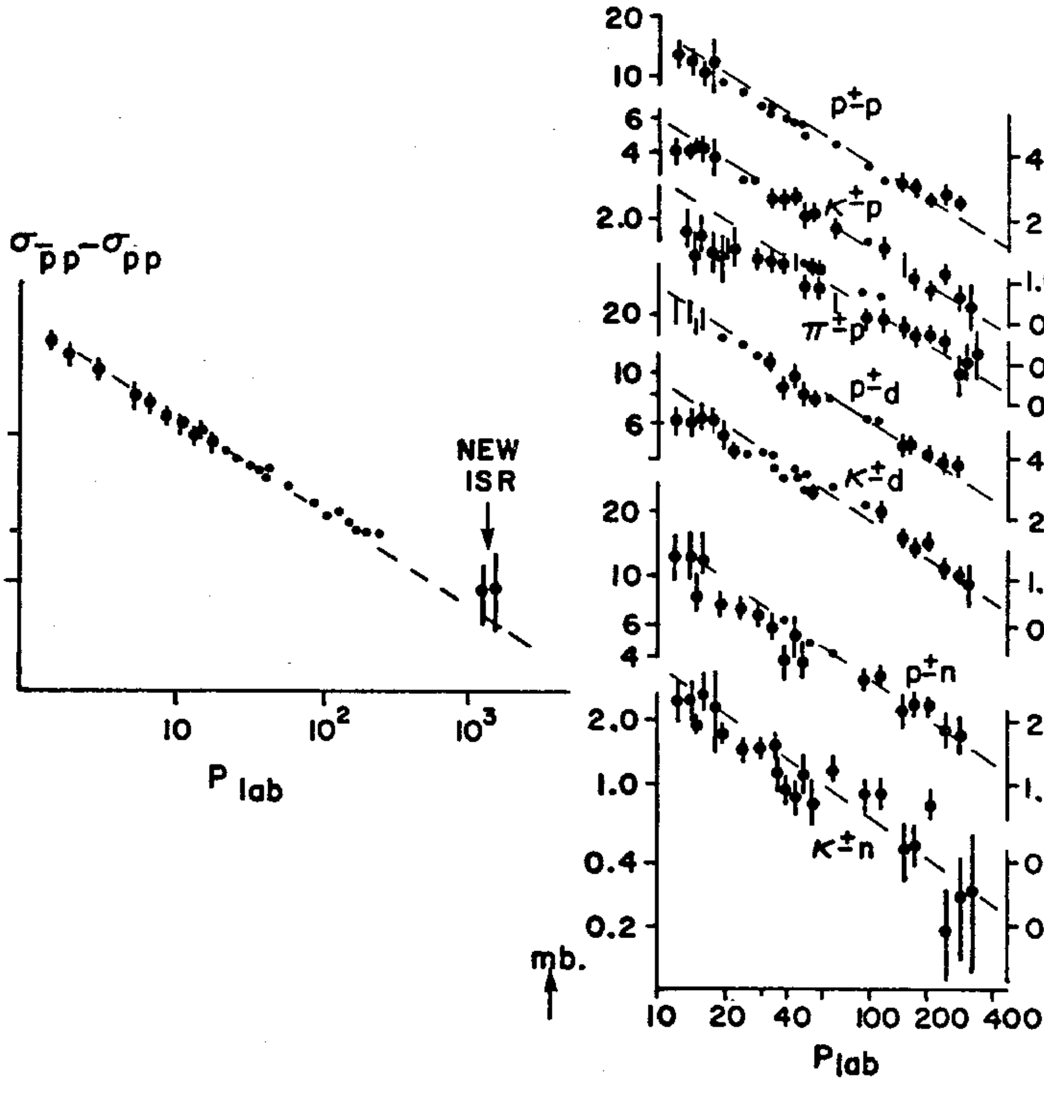

Fig. 8. The power law decrease of particle-antiparticle cross-section differences.

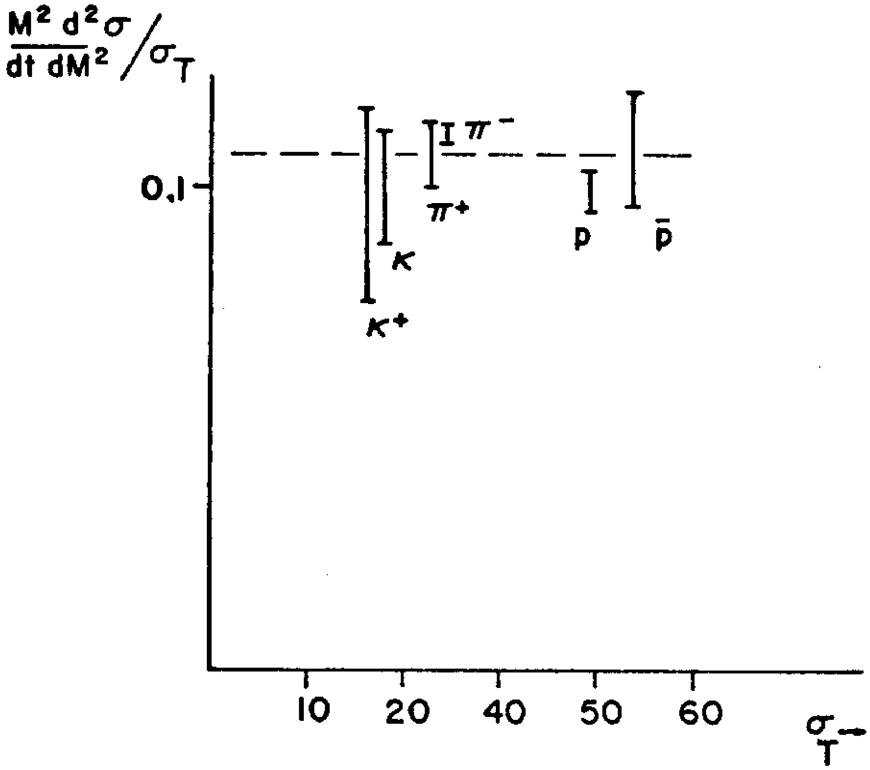

Fig. 9. Factorization tested by comparing large mass diffractive excitation with total cross-sections.

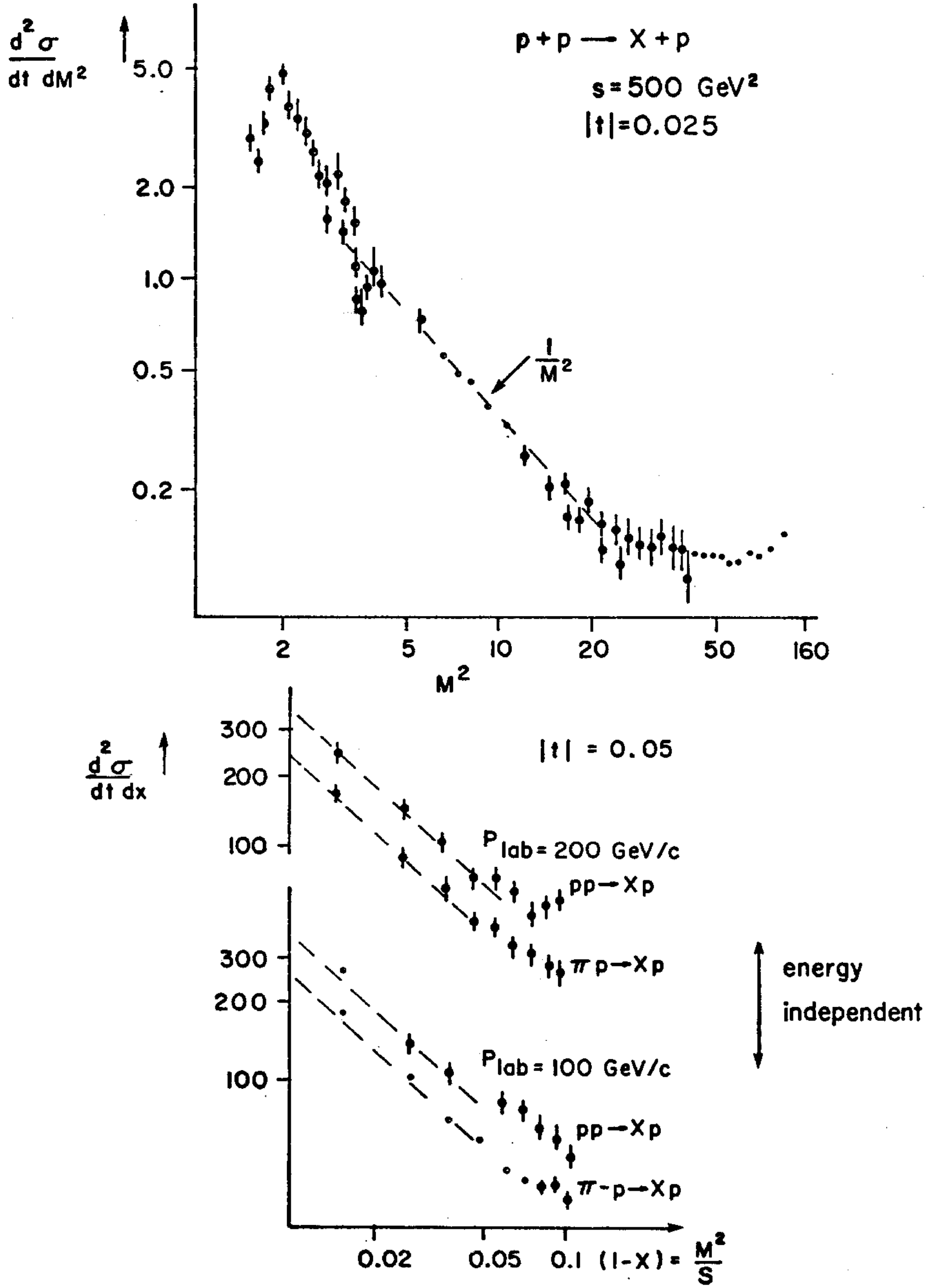

Fig. 10. Energy independence and $1/M^2$ behavior of large mass diffractive excitation.

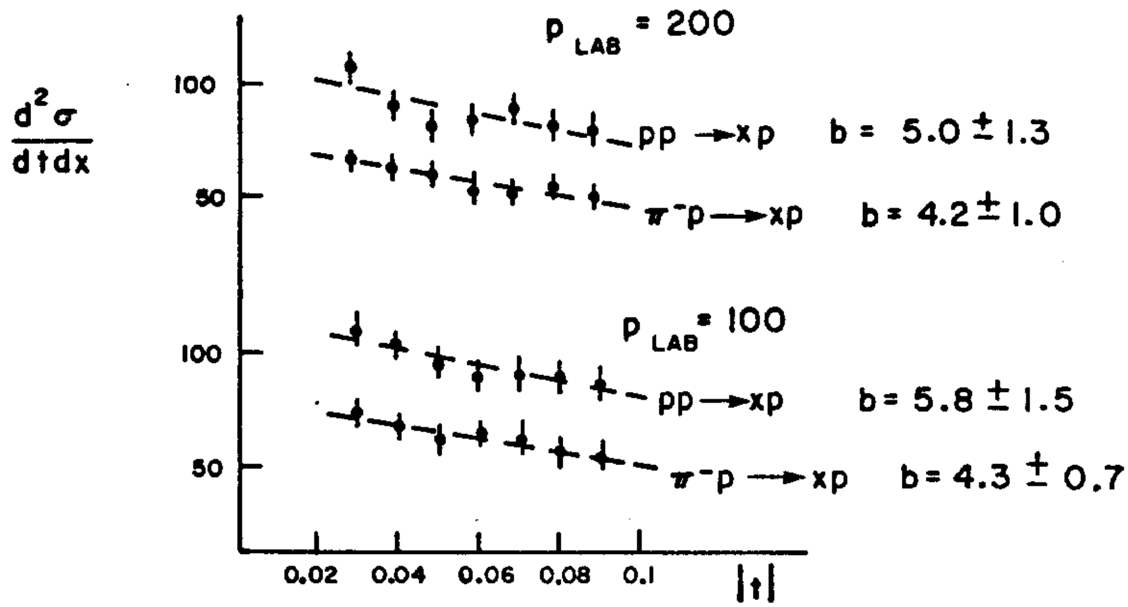

Fig. 11. Inclusive slope parameters - comparing (1) and (8) gives $g_{PPP}(t) \sim e^{bt-1/2b_{el}t}$ in the approximation $\alpha'_P=0$ if b_{el} is the corresponding slope parameter for elastic scattering. From Fig. 2 we see that g_{PPP} is approximately t-independent.

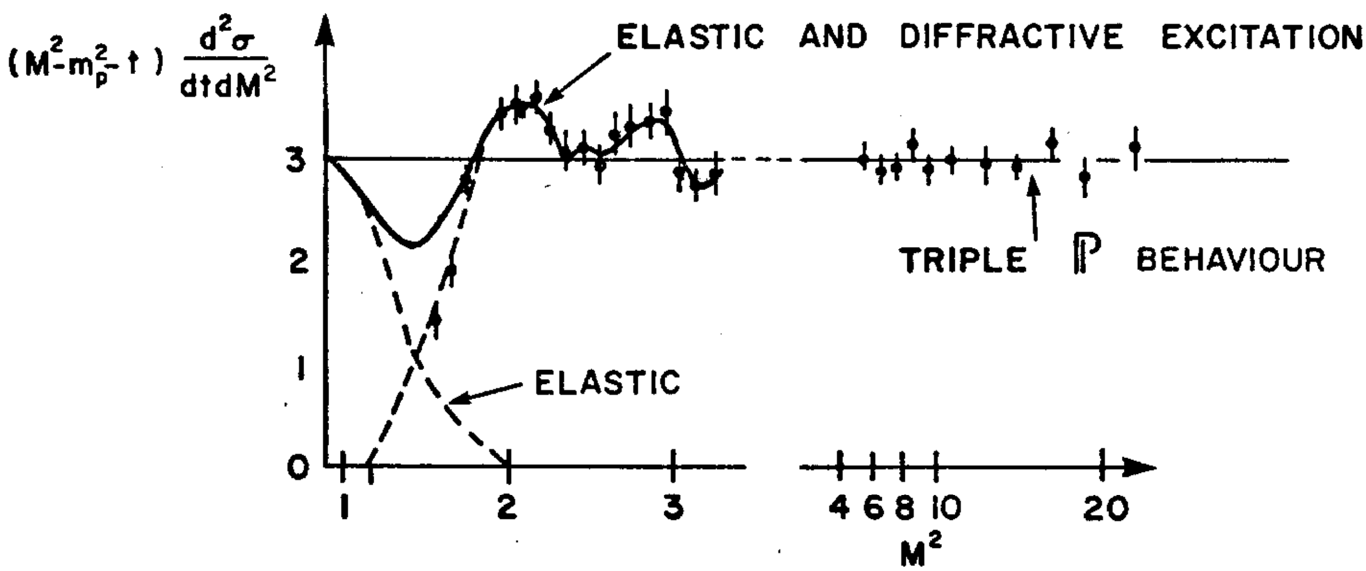

Fig. 12. The finite mass sum rule - triple P cross-section extrapolated to low missing mass averages the sum of the elastic and low mass excitation.

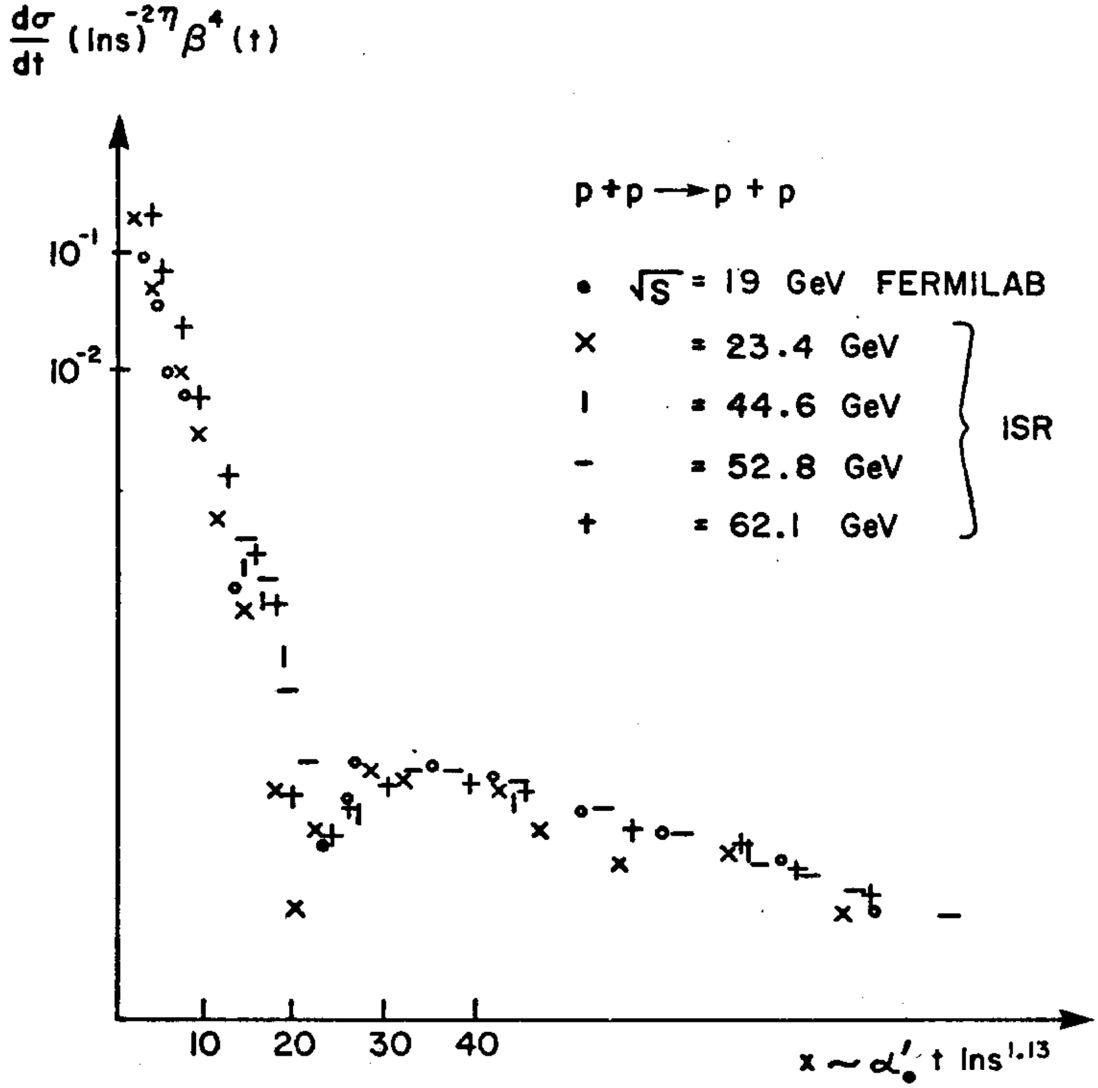

Fig. 13. Test of Critical Pomeron scaling of the elastic diffraction peak.

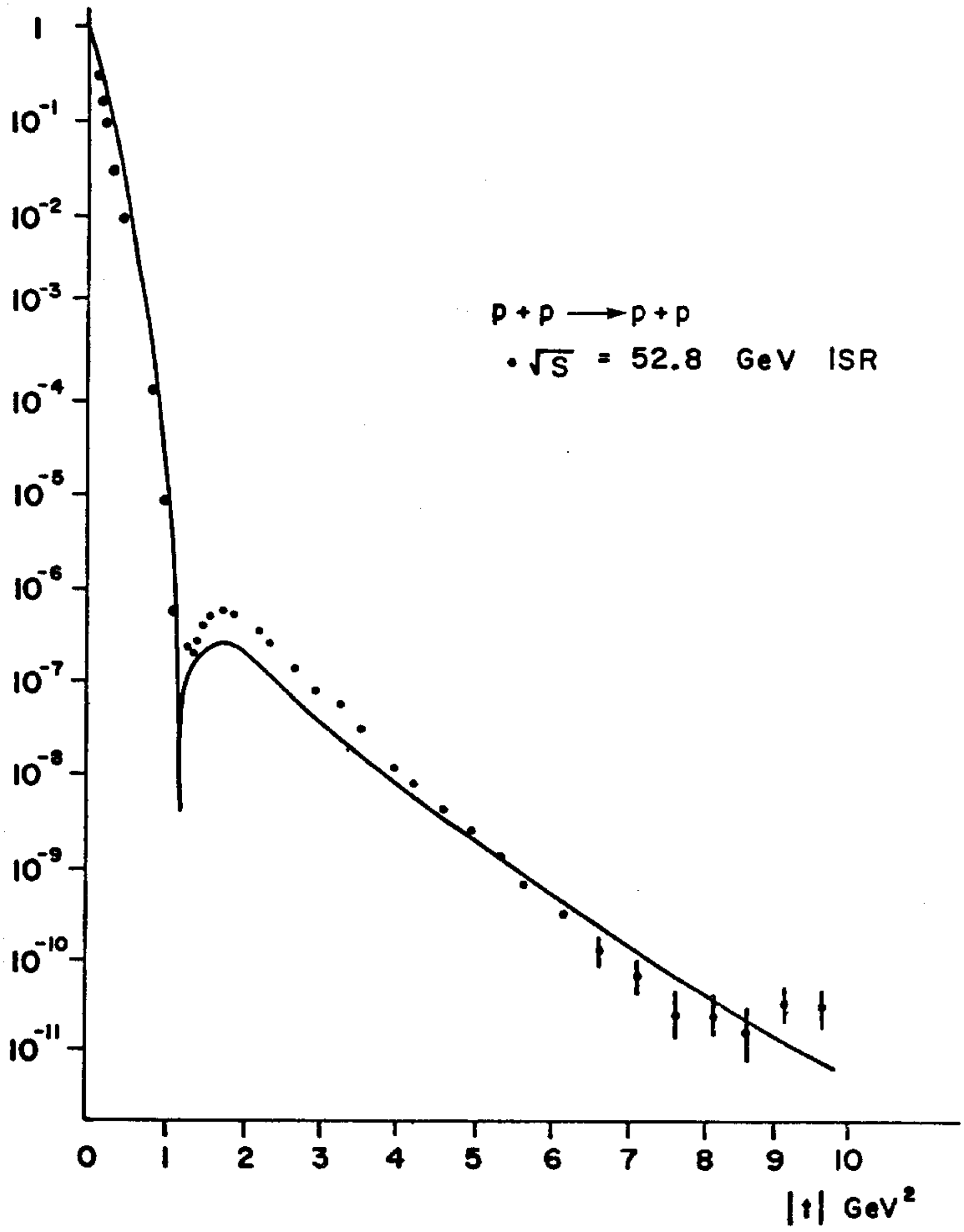

Fig. 14. Comparison of the Critical Pomeron scaling function with the p-p elastic diffraction peak.

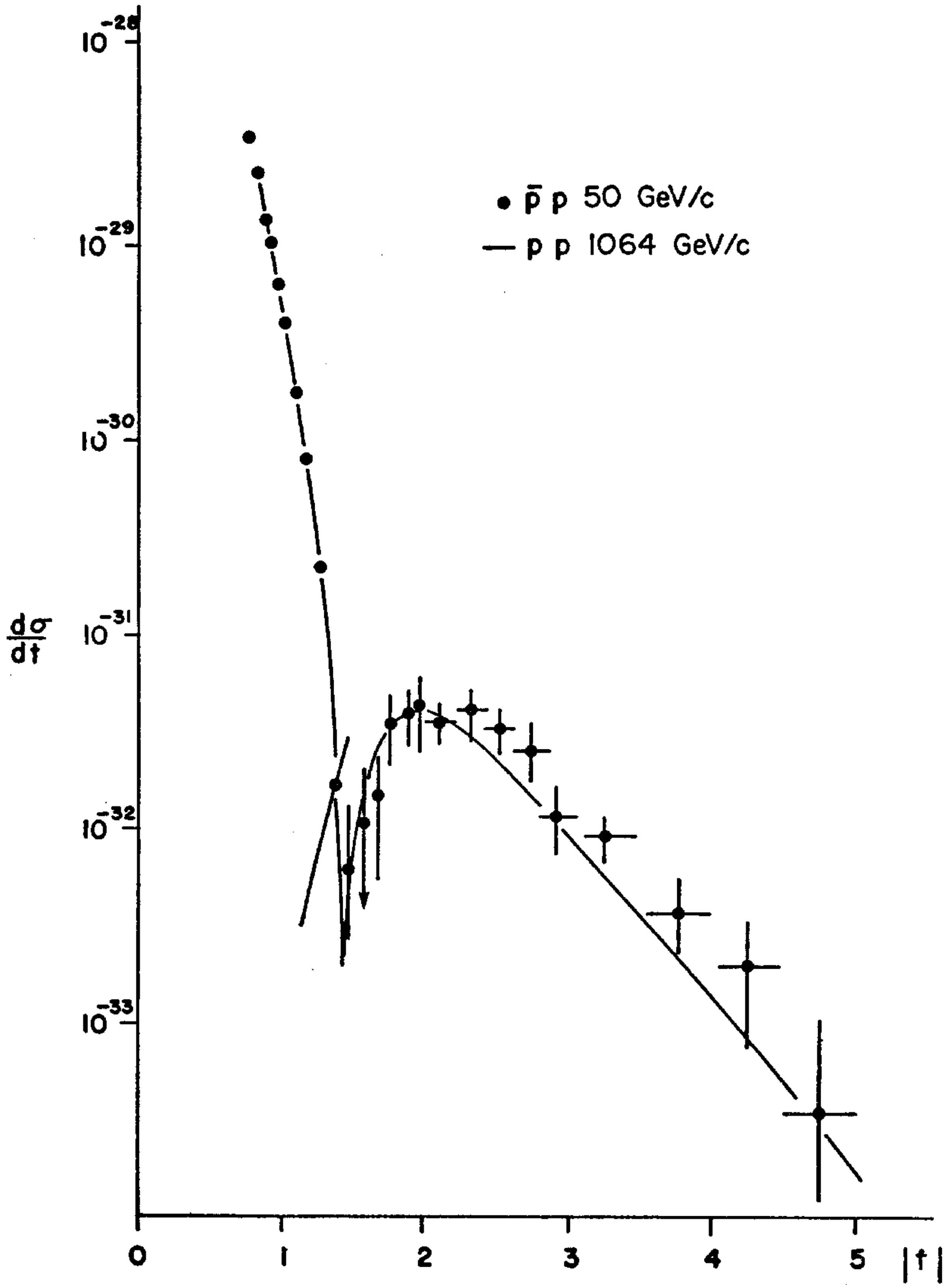

Fig. 15. Comparison of the $\bar{p}p$ diffraction peak with the p-p diffraction peak.

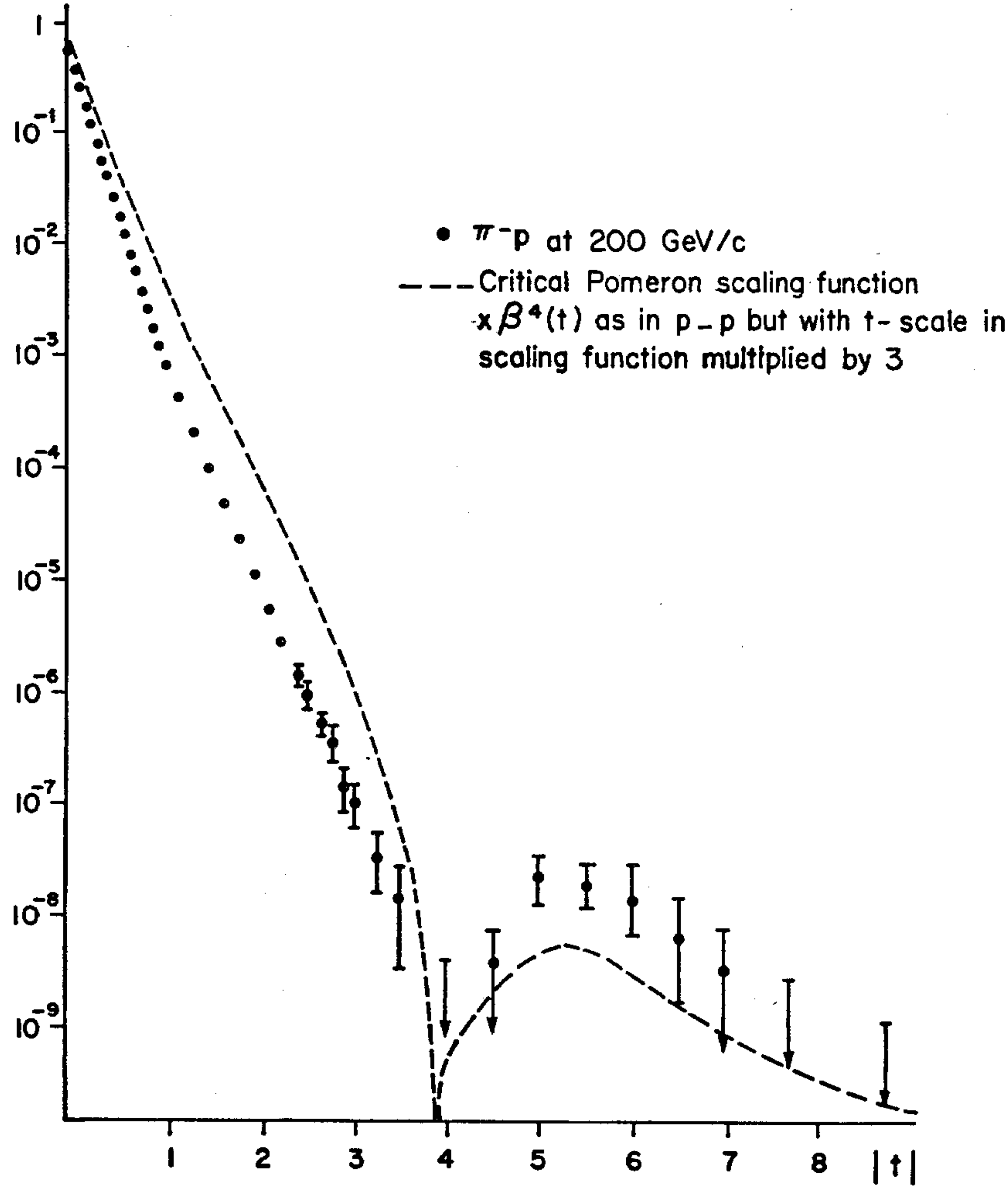

Fig. 16. The π^-p diffraction pattern compared with the critical Pomeron scaling function.

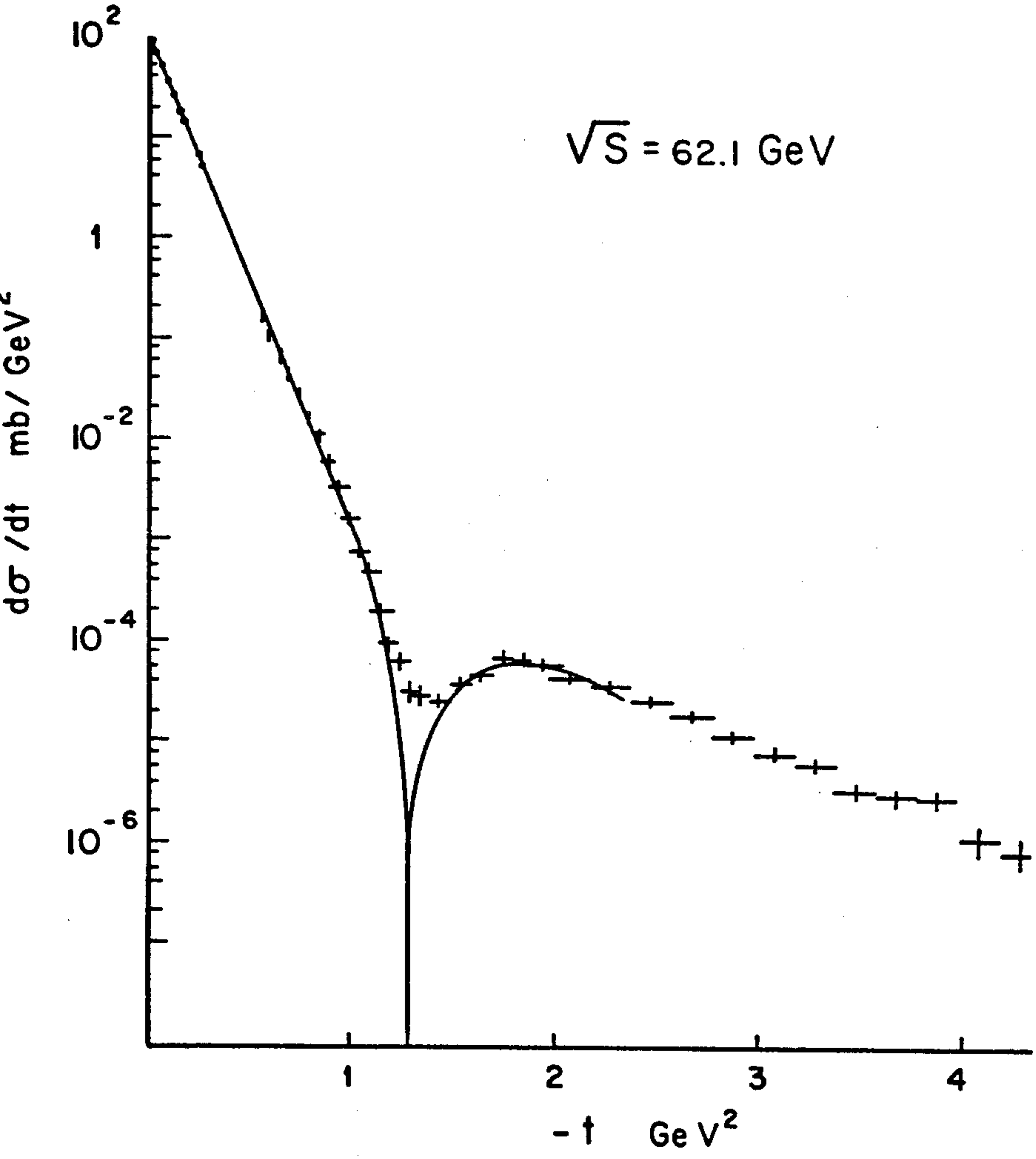

Fig. 17. The fit to the highest ISR energy results.

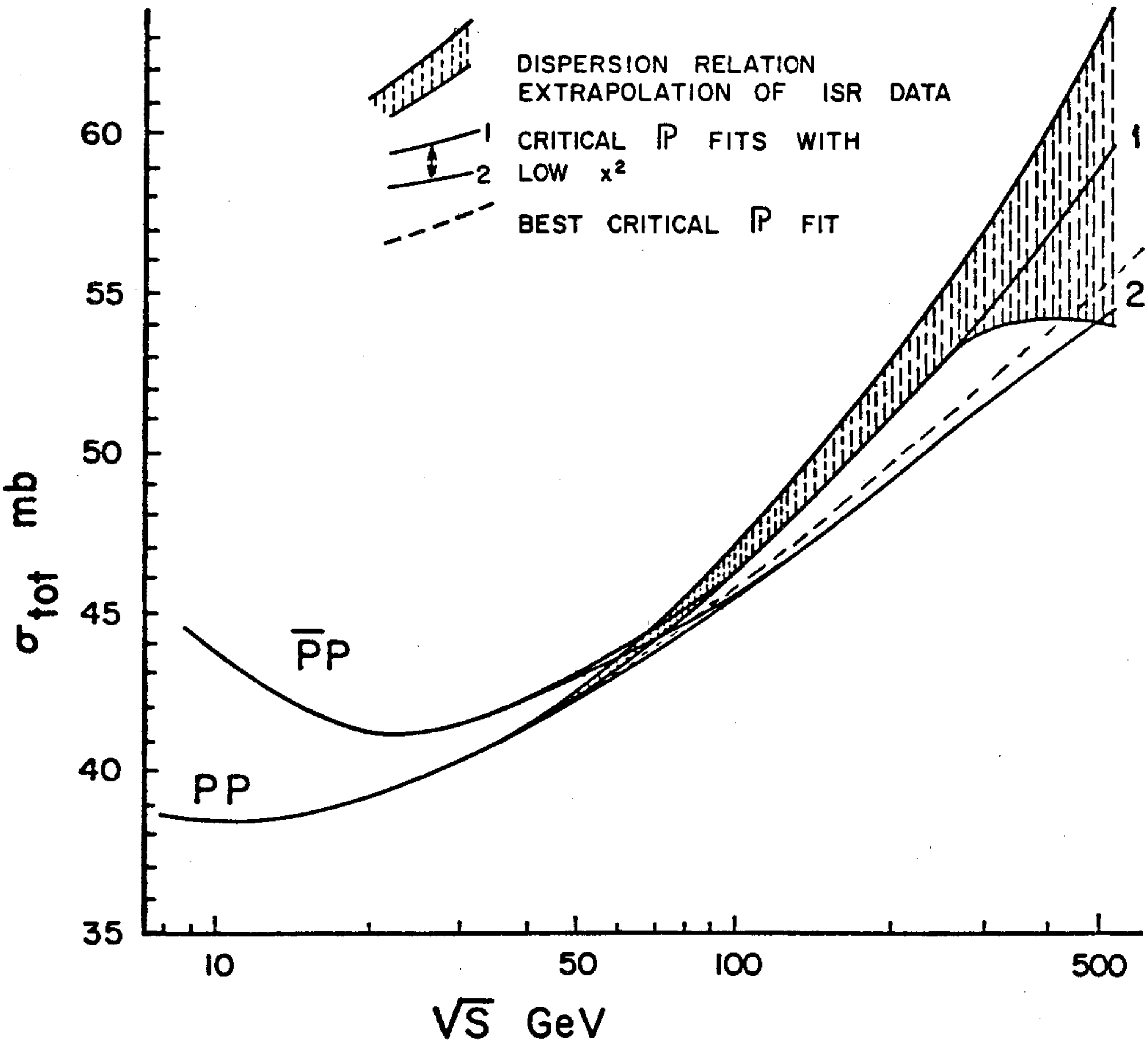

Fig. 18. Critical P extrapolation of p-p and $\bar{p}$-p total cross-sections.

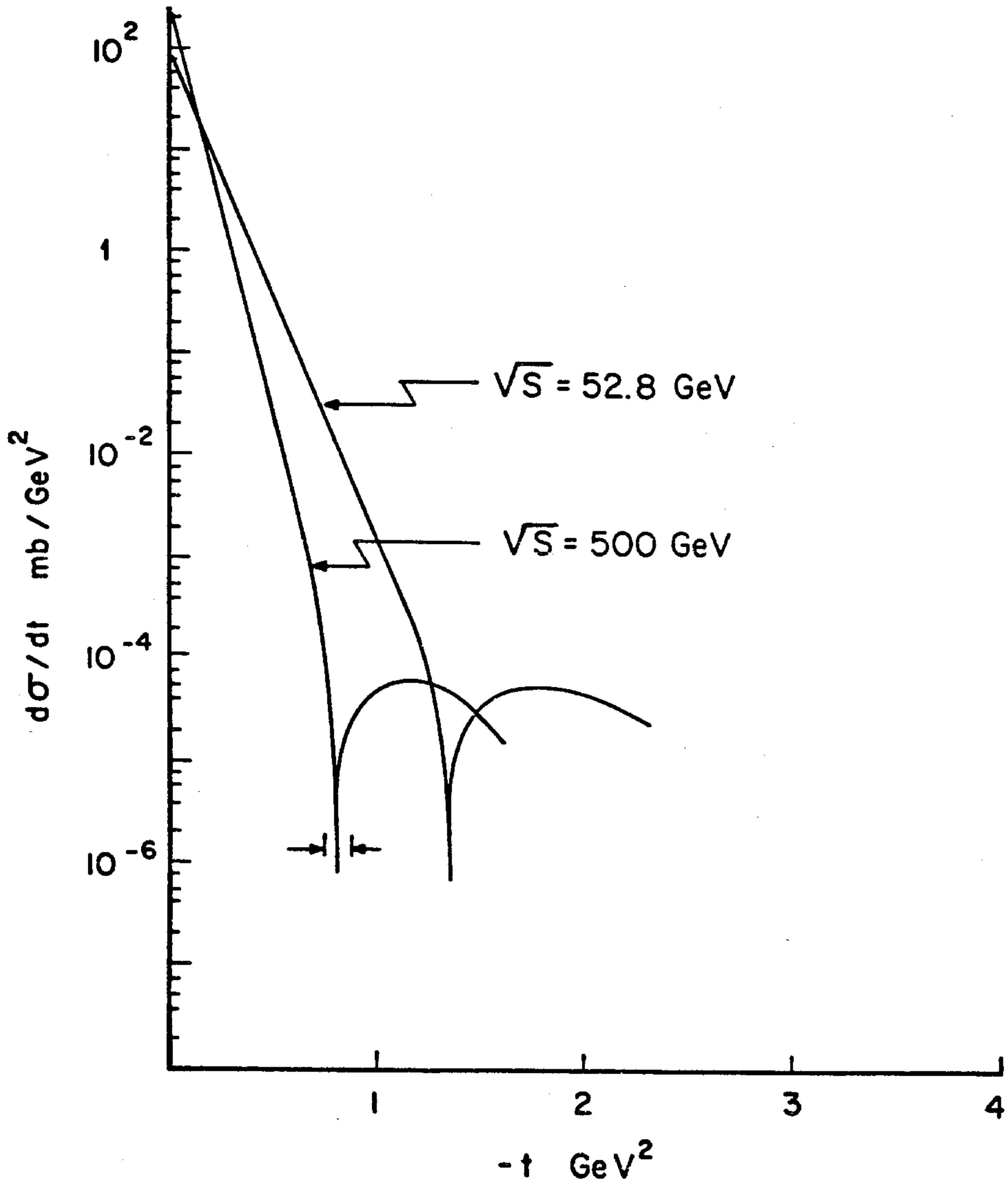

Fig. 19. Critical Pomeron prediction for the $\bar{p}$-p differential cross-section.

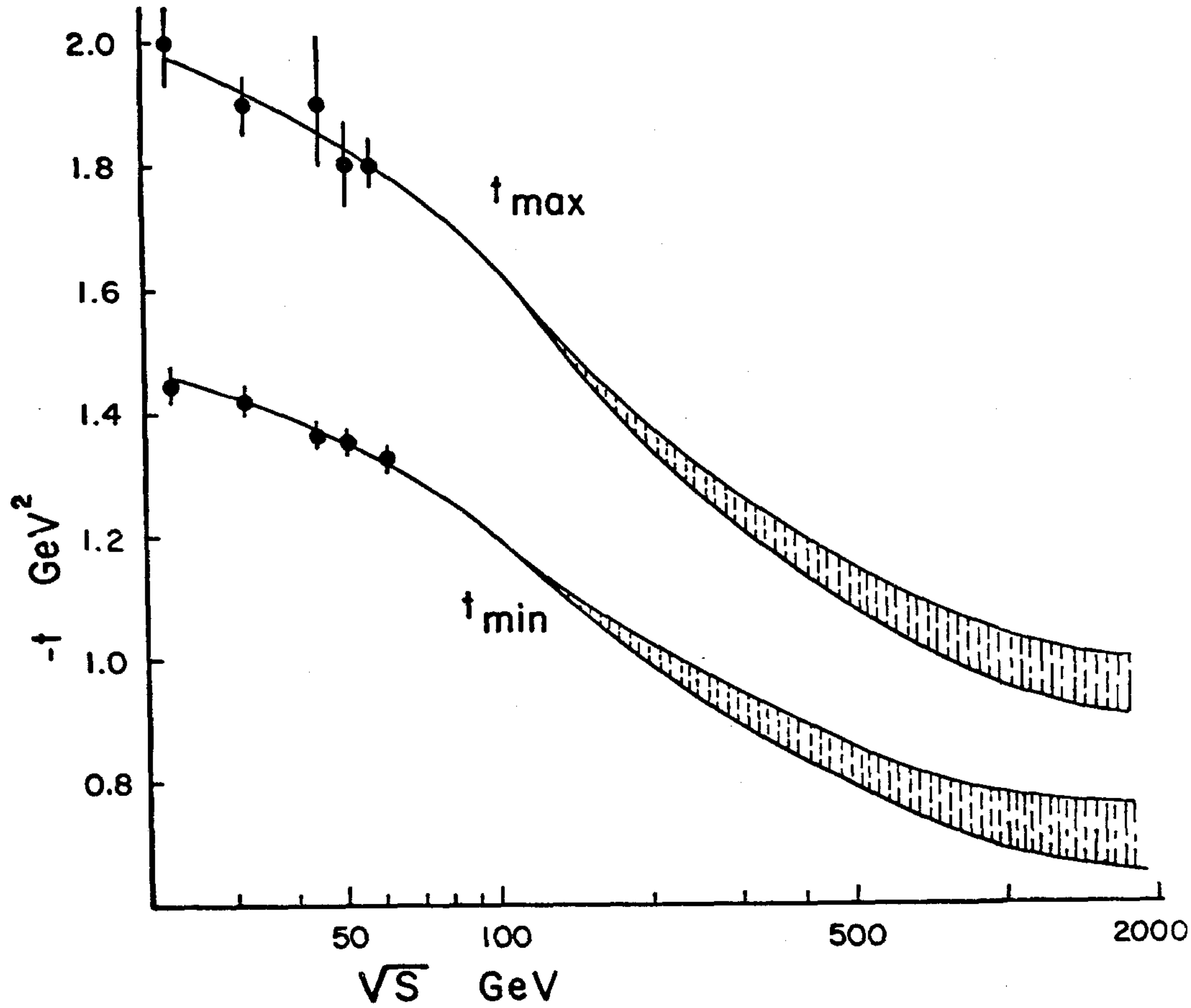

Fig. 20. Critical Pomeron prediction for the movement of the diffraction minimum and maximum.

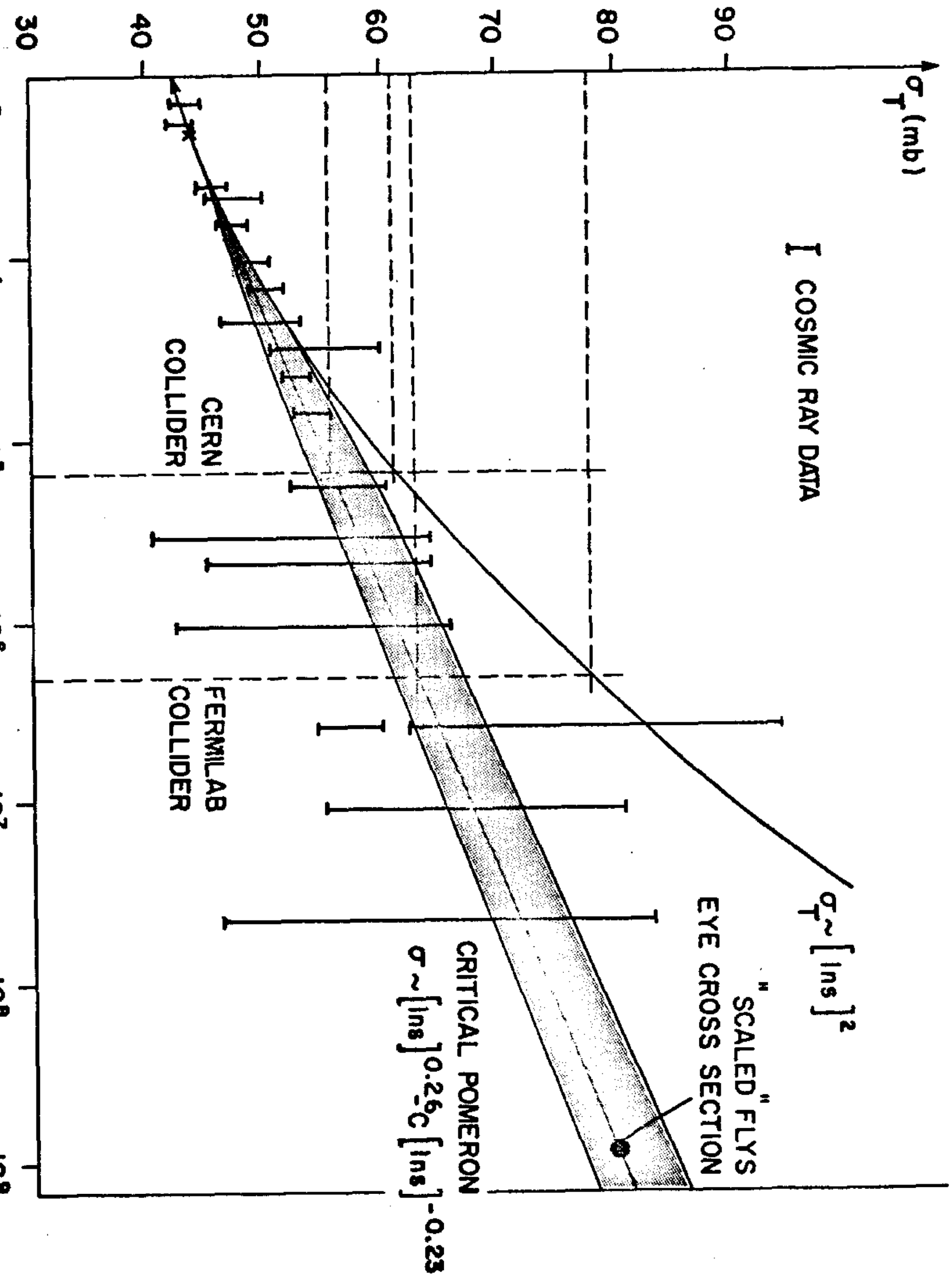

Fig. 21. Total cross-section predictions compared with Cosmic Ray data.

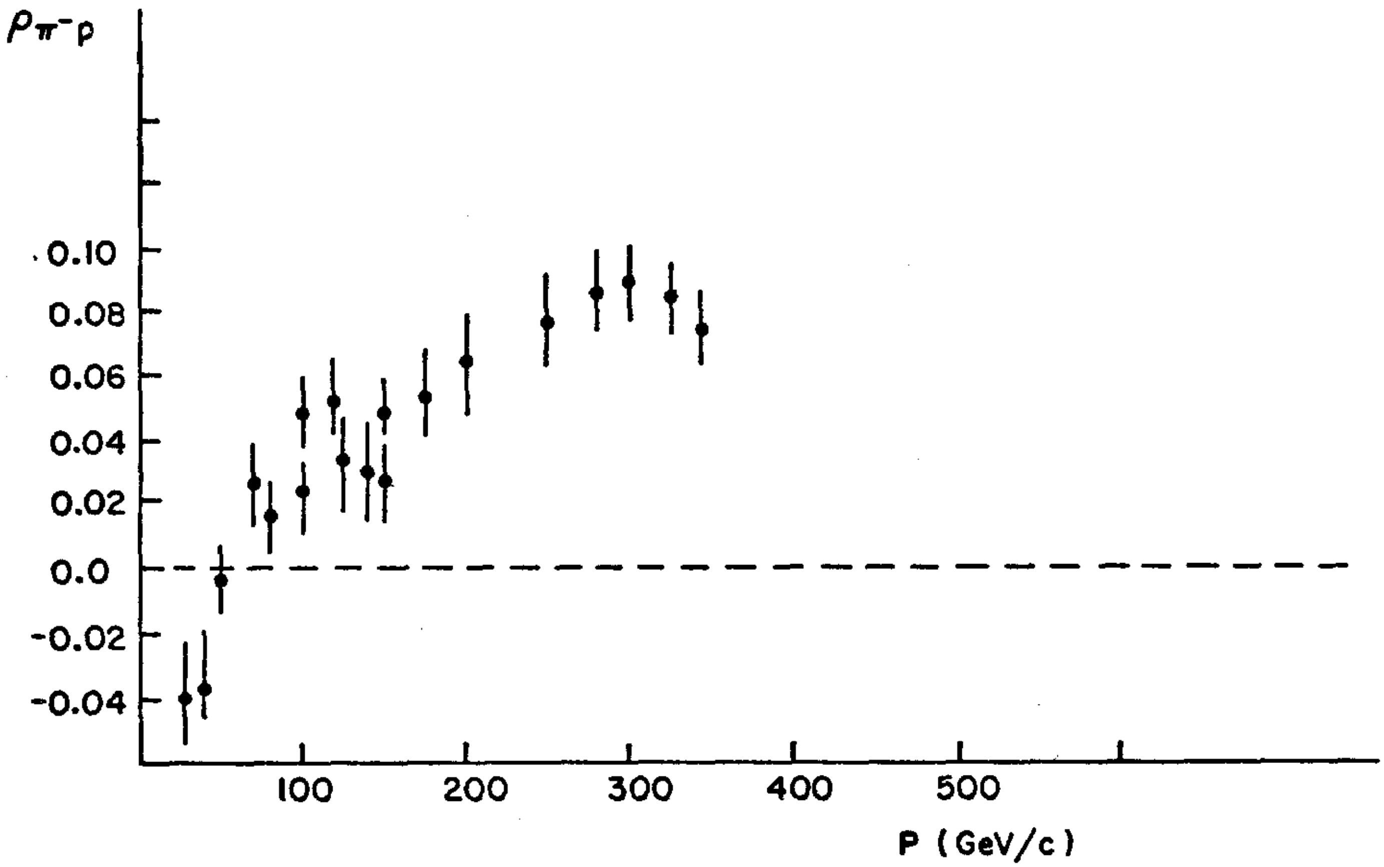

Fig. 22. The π^-p ratio of real to imaginary parts.

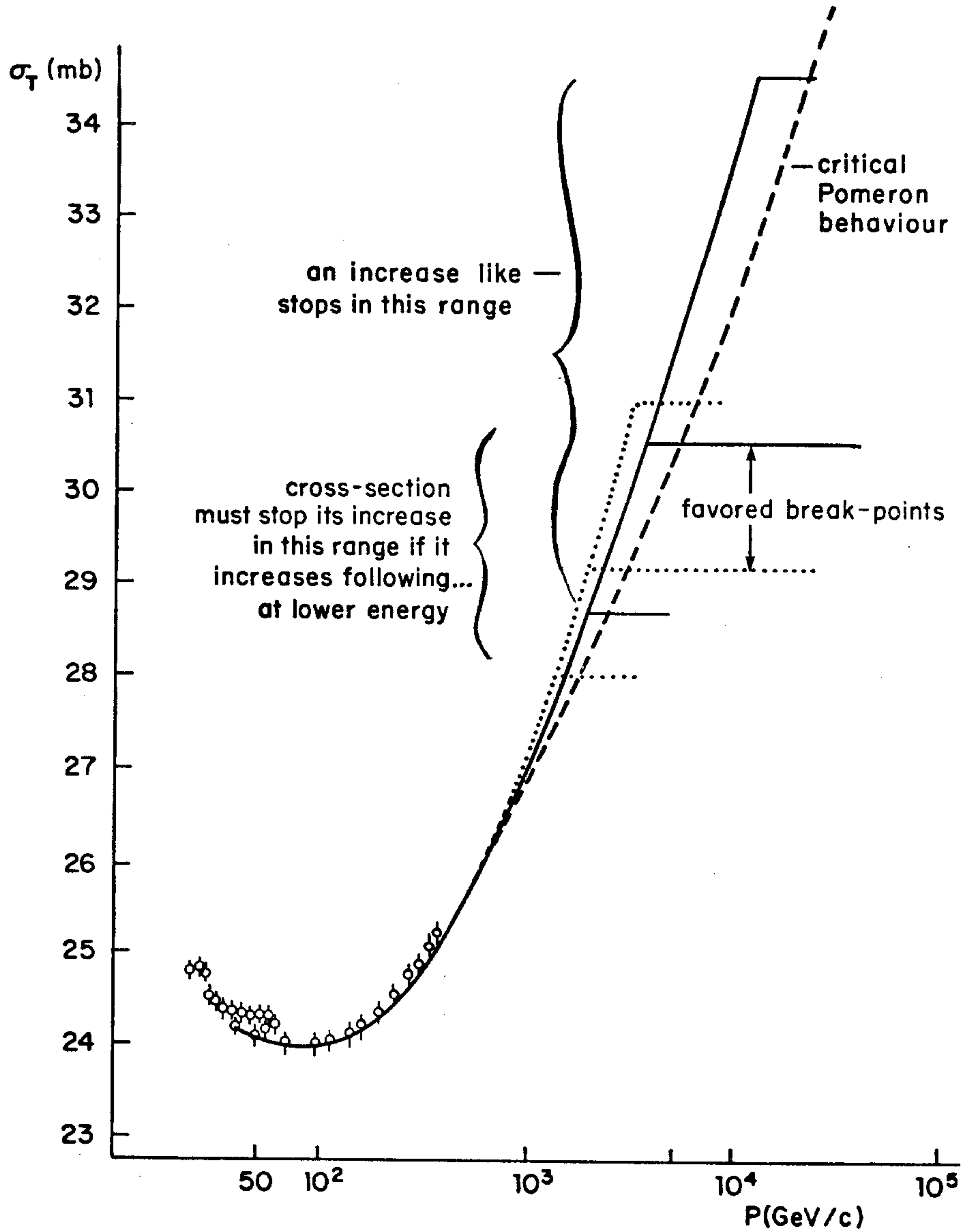

Fig. 23. Dispersion relation constraint on the rise of the $\pi^- p$ total cross-section.

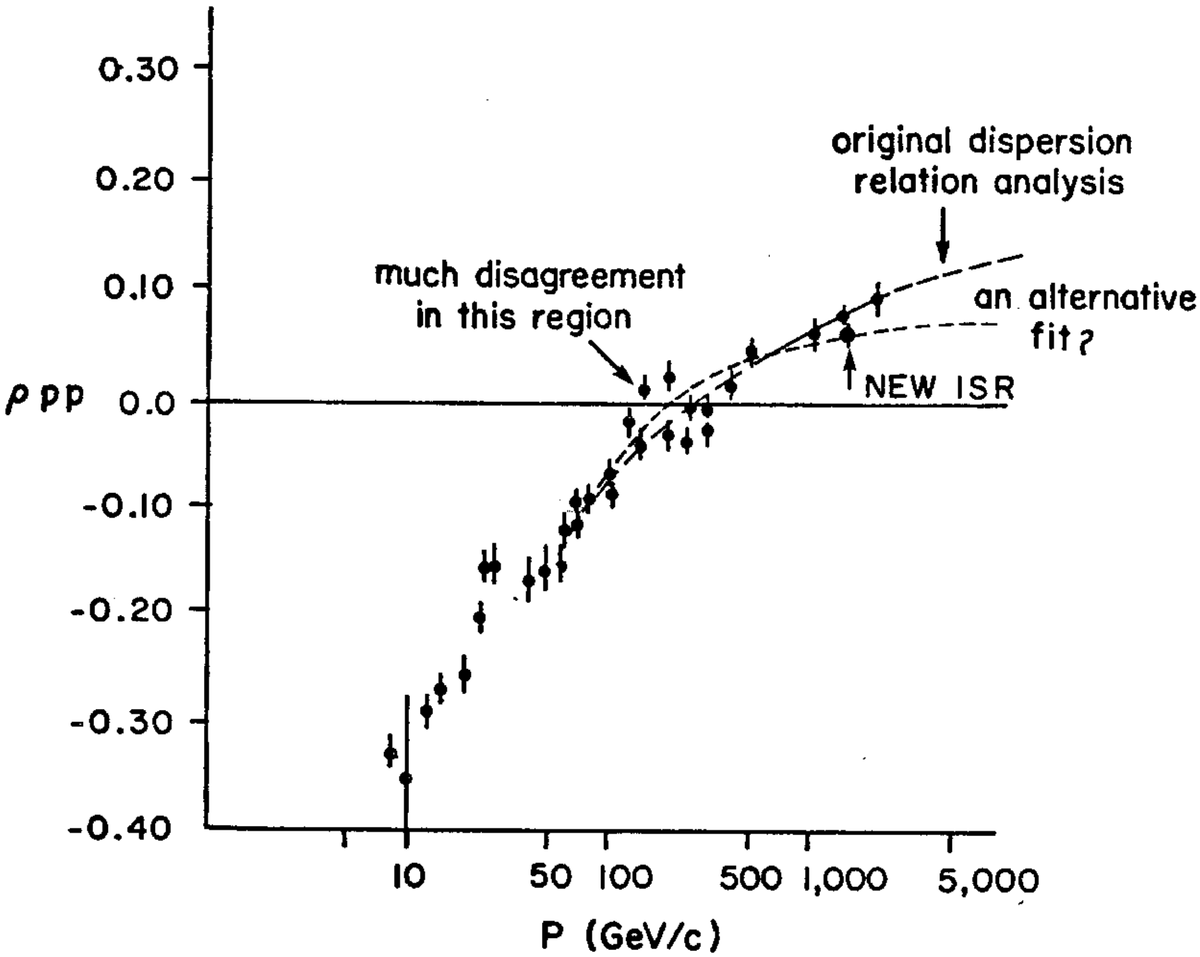

Fig. 24. ρ_{pp} including a new ISR measurement.

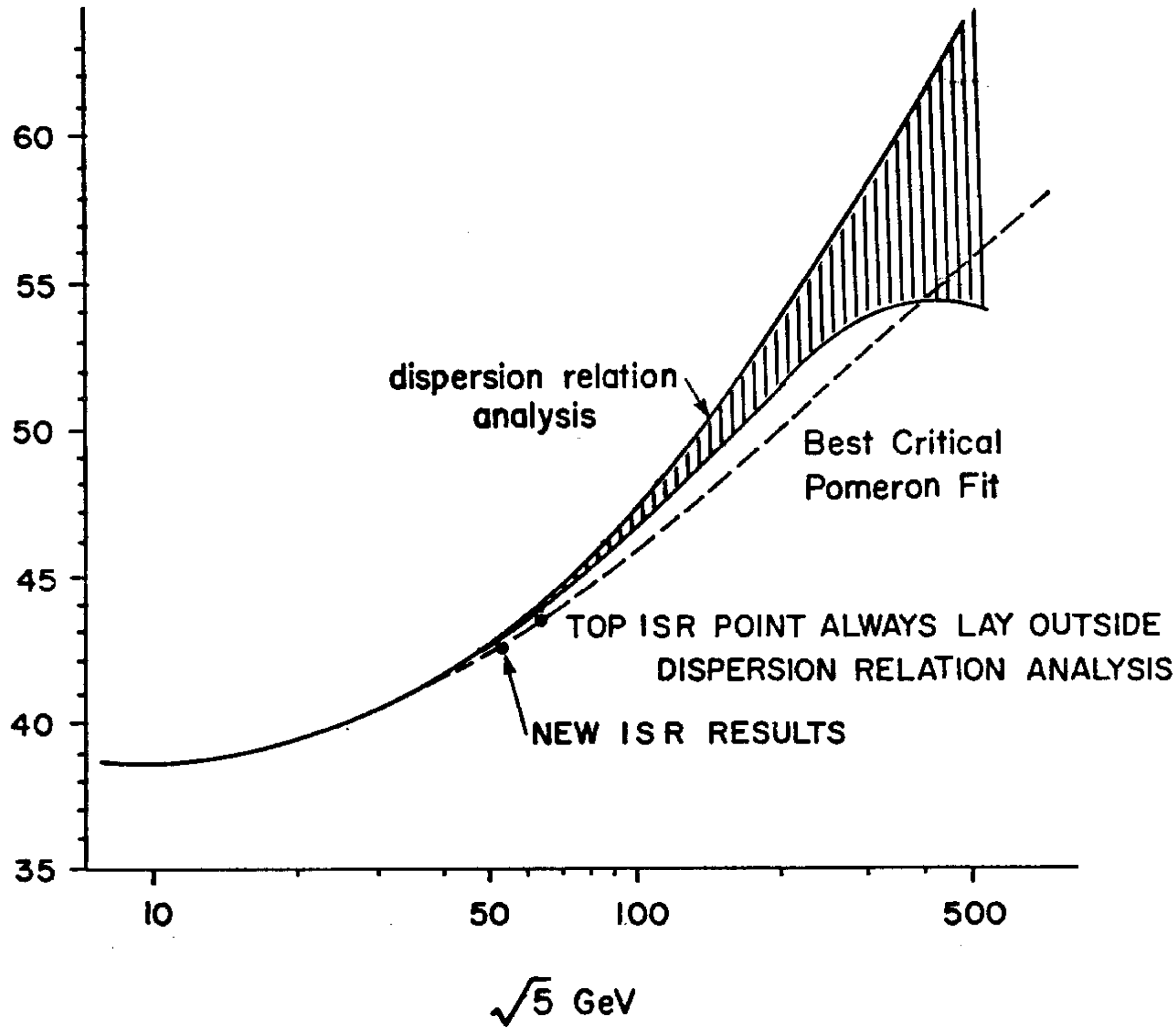

Fig. 25. Comparison of new ISR results for the p-p total cross-section with the dispersion relation analysis.

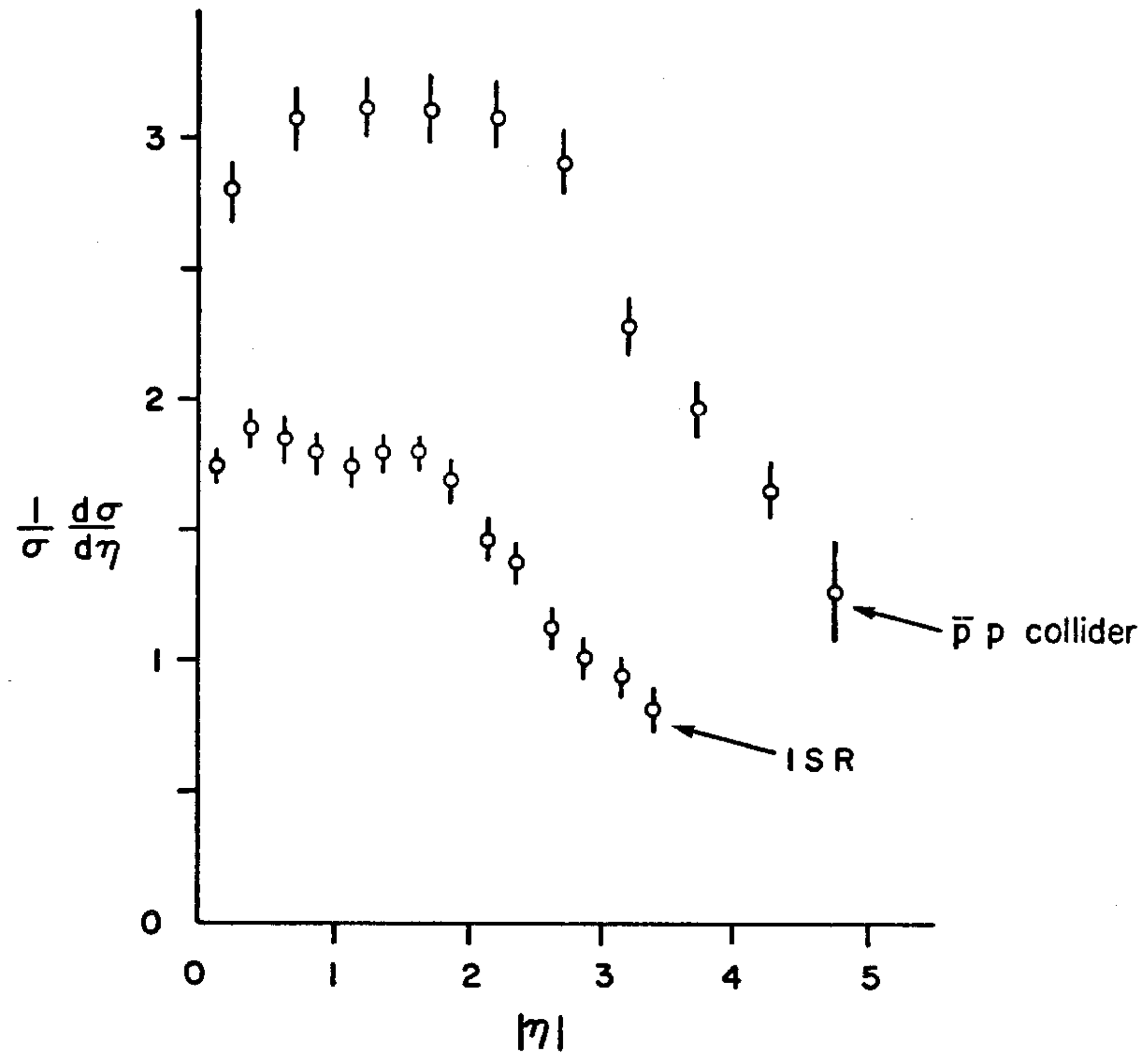

Fig. 26. The rise of the central plateau from the ISR to the CERN collider. The plateau is not broadening as it rises, as a naive phase-space model would predict.

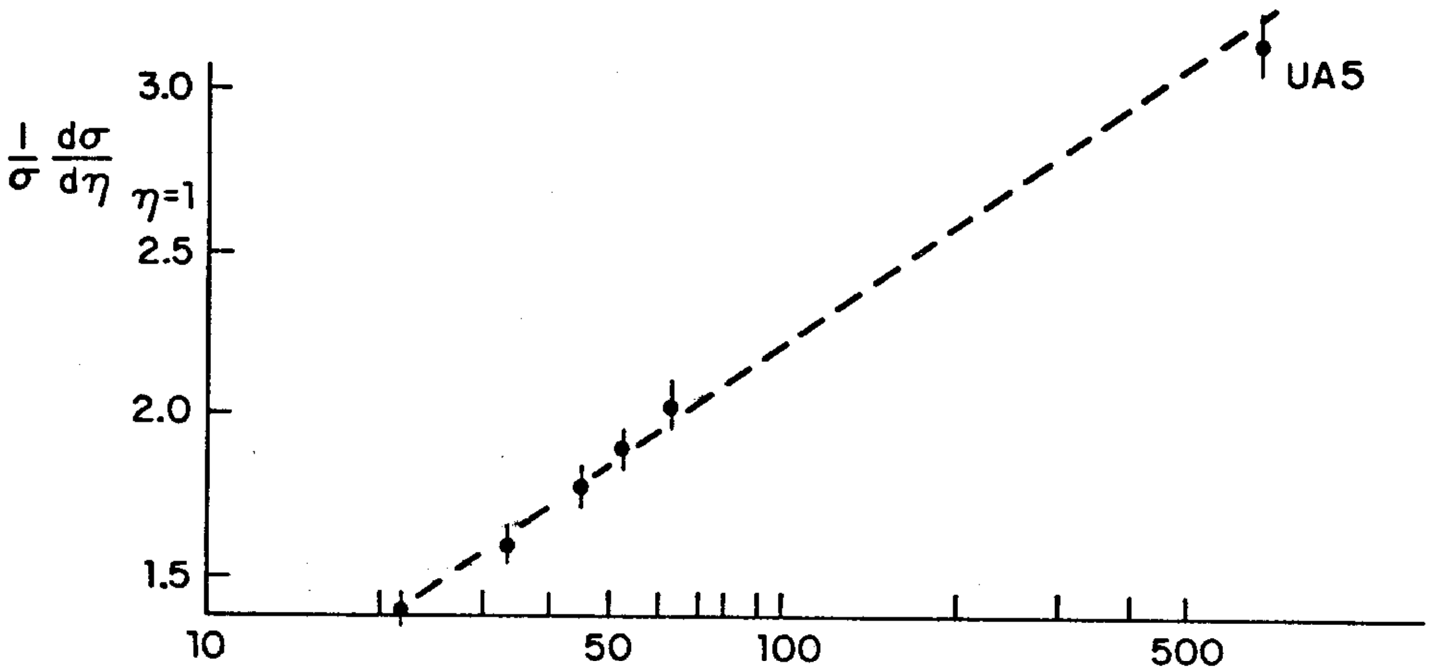

Fig. 27. The collider rise of the central plateau fits on a logarithmic extrapolation of the ISR results as predicted by the Critical Pomeron relation $d\sigma/d\eta \sim \sigma_T^2$.

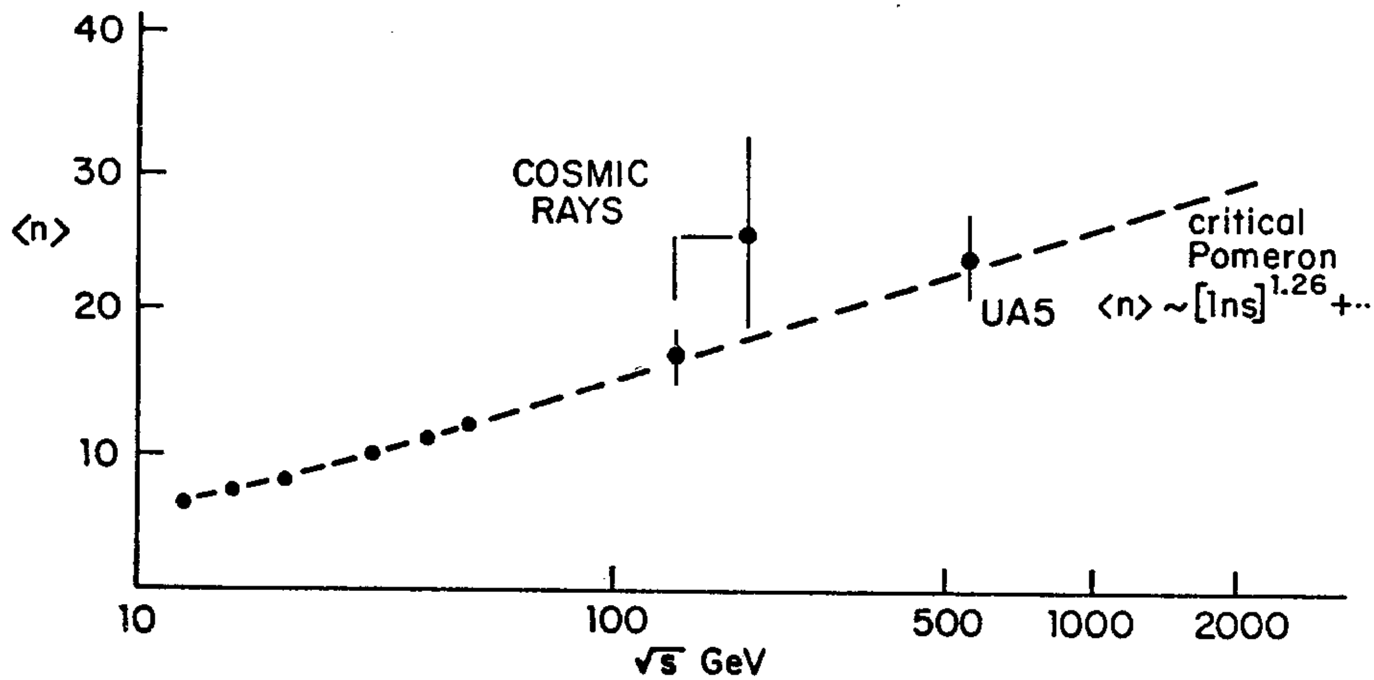

Fig. 28. The comparison of the collider average multiplicity and a rough critical Pomeron extrapolation.

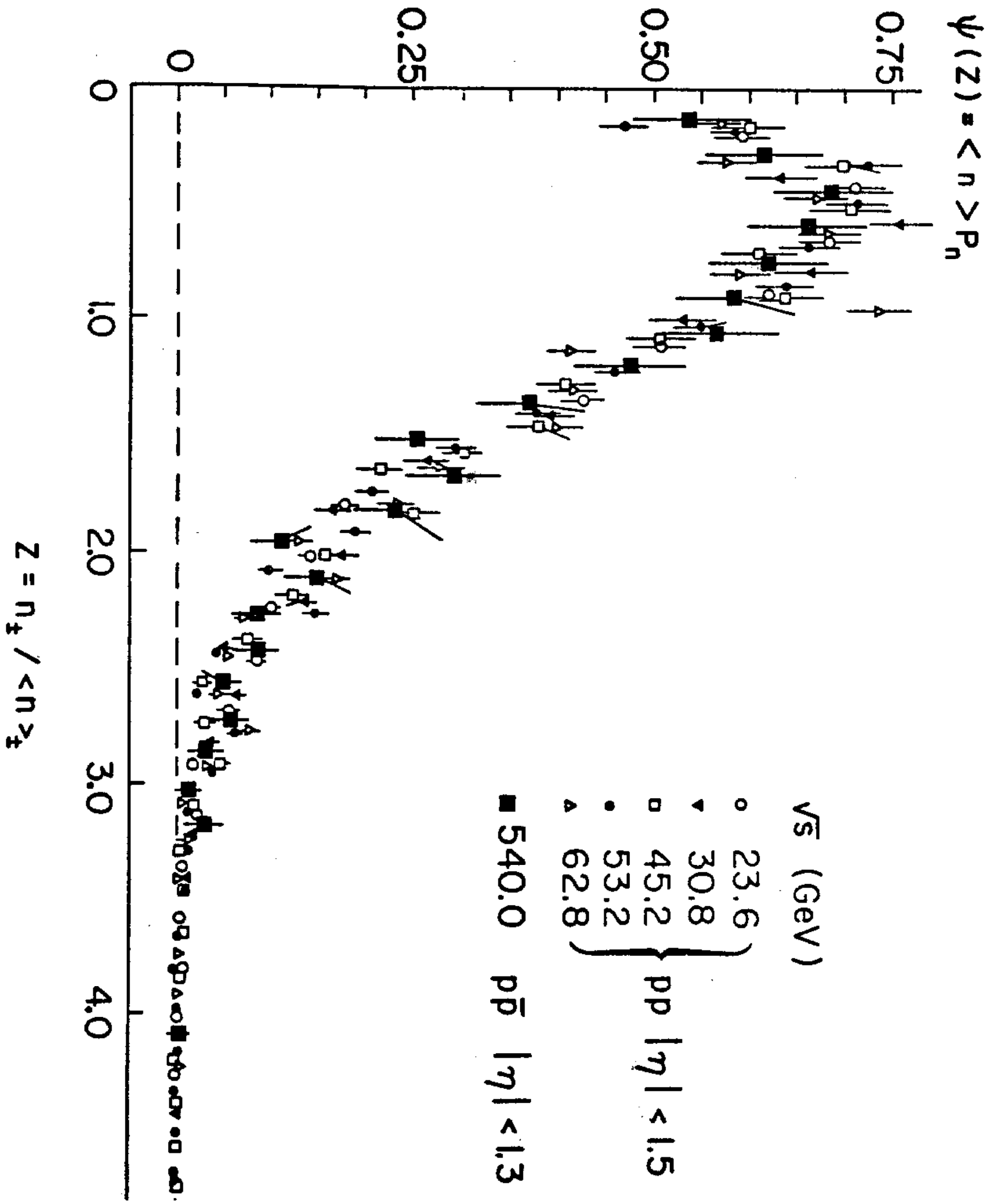

Fig. 29. The UA1 multiplicity distribution superimposed on that found at the ISR - suggesting that at least the lowest multiplicity moments have changed little.

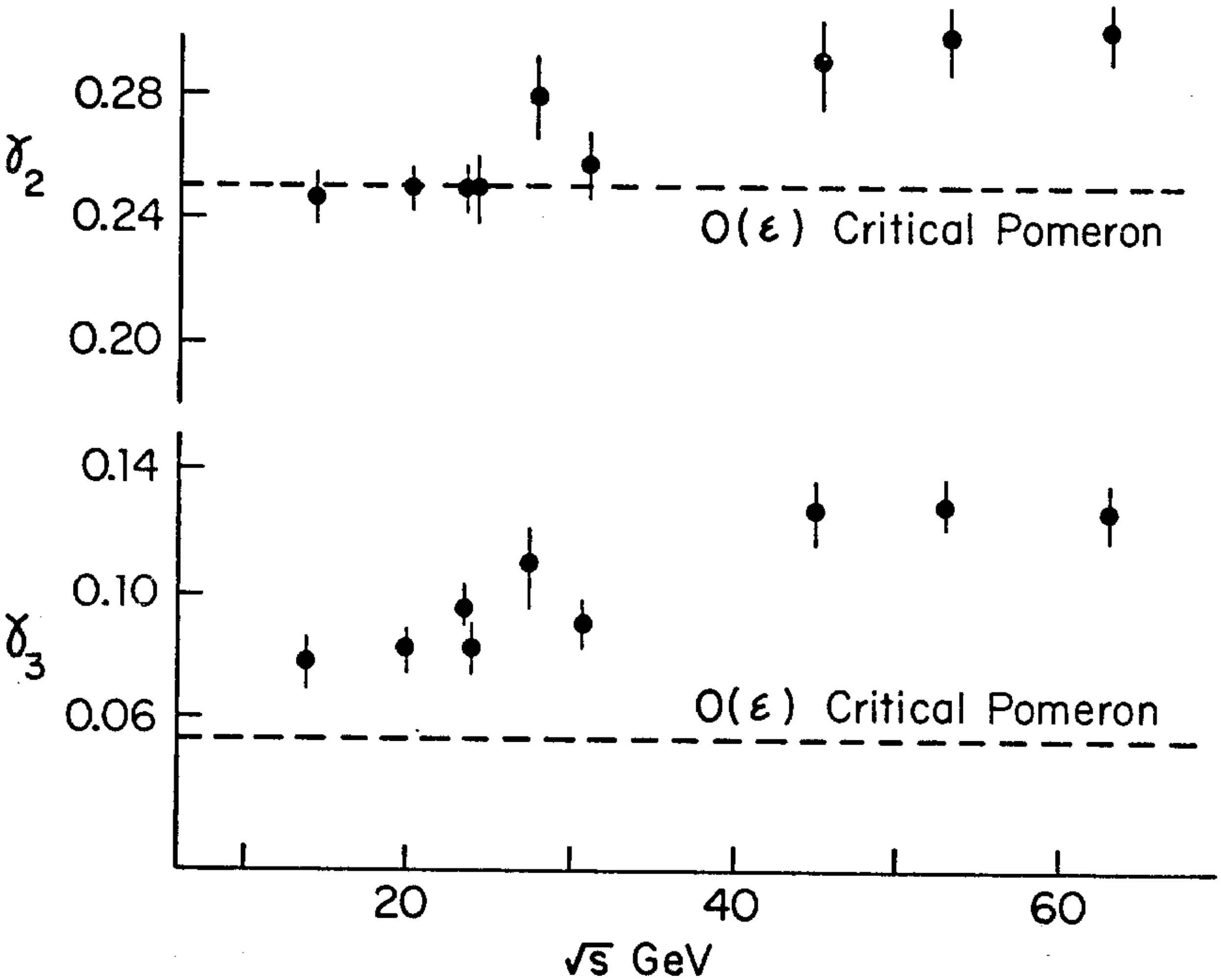

Fig. 30. Experimental results for the "γ" multiplicity moments and the "O(ε) Critical Pomeron predictions - which are certainly an underestimate.

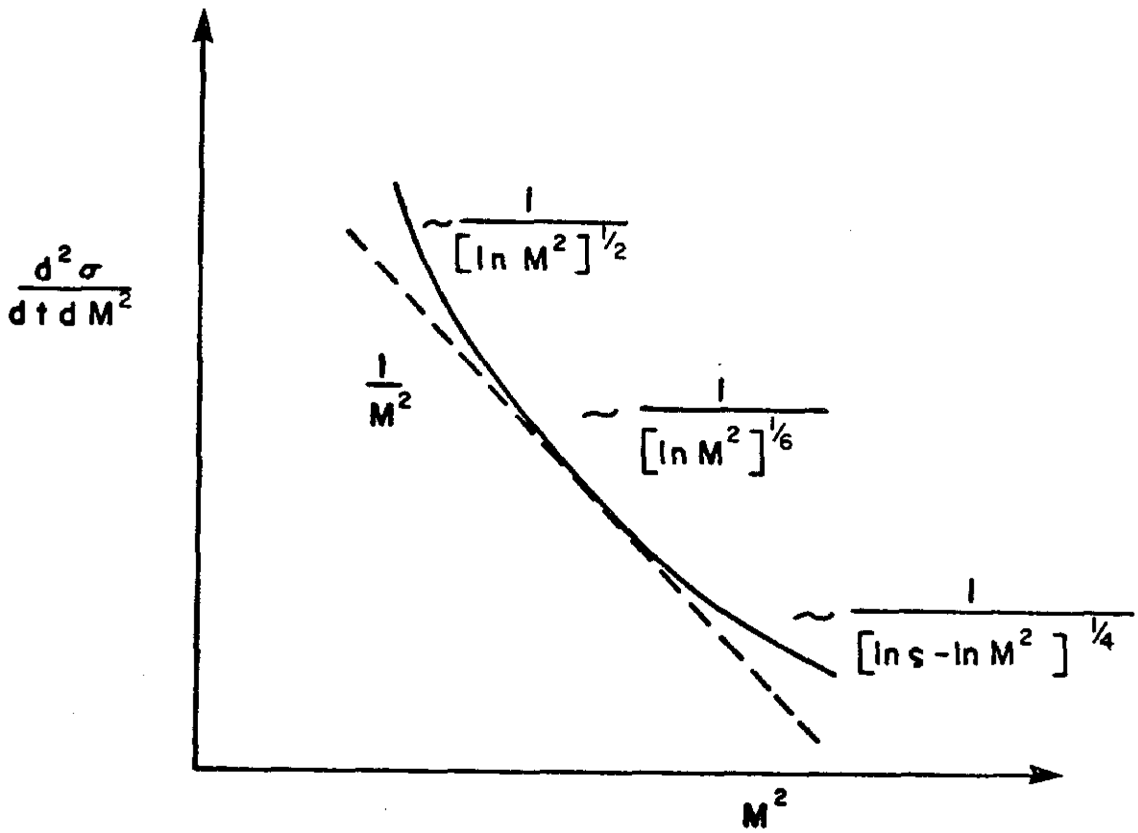

Fig. 31. Asymptotic logarithmic modification of the triple Pomeron distribution (calculated to $O(\varepsilon)$).

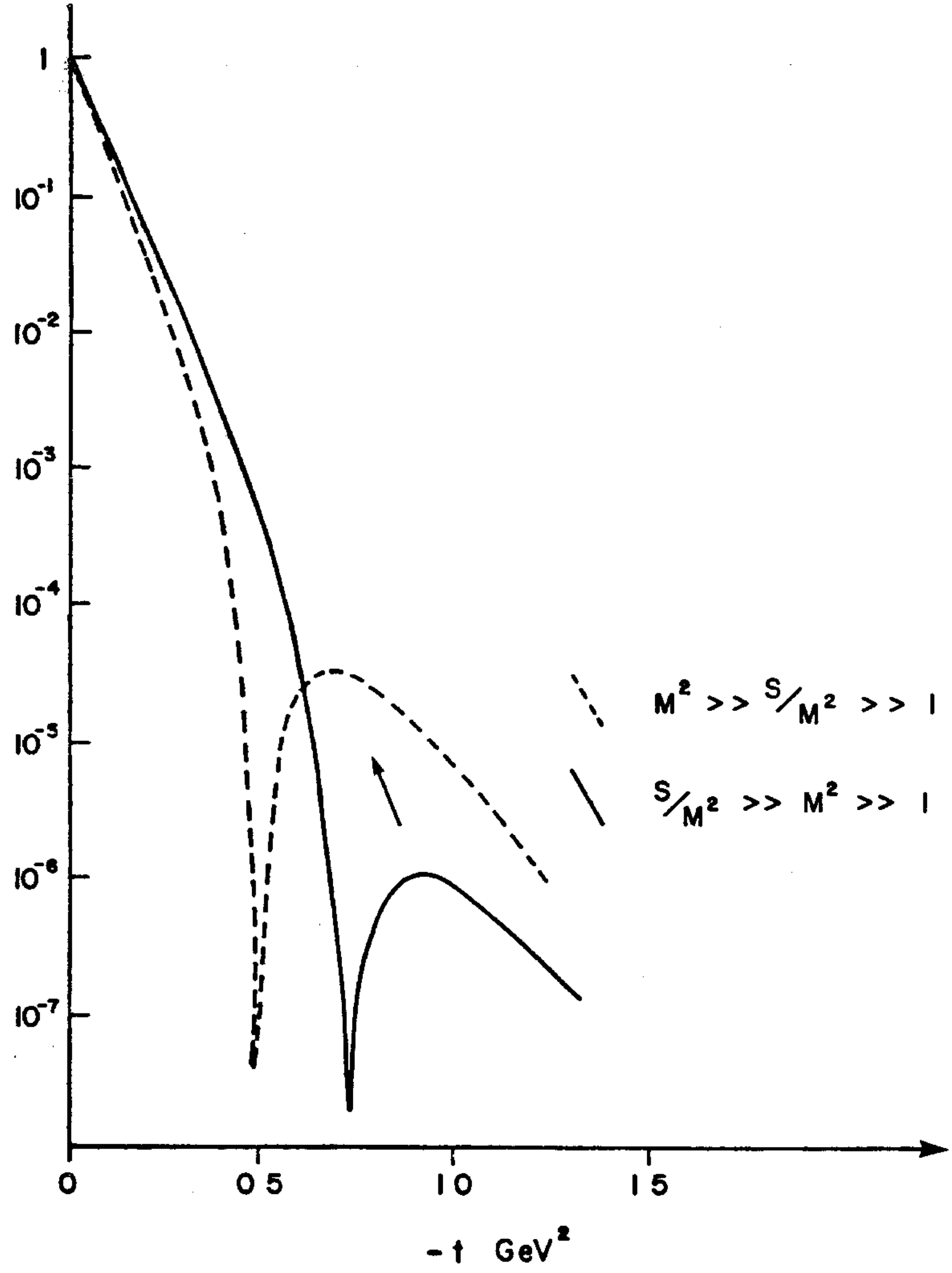

Fig. 32. Predicted movement of $M^2\, d^2\sigma/dtdM^2$ plotted against t as M^2 increased through the triple Pomeron region - again an $O(\varepsilon)$ calculation.

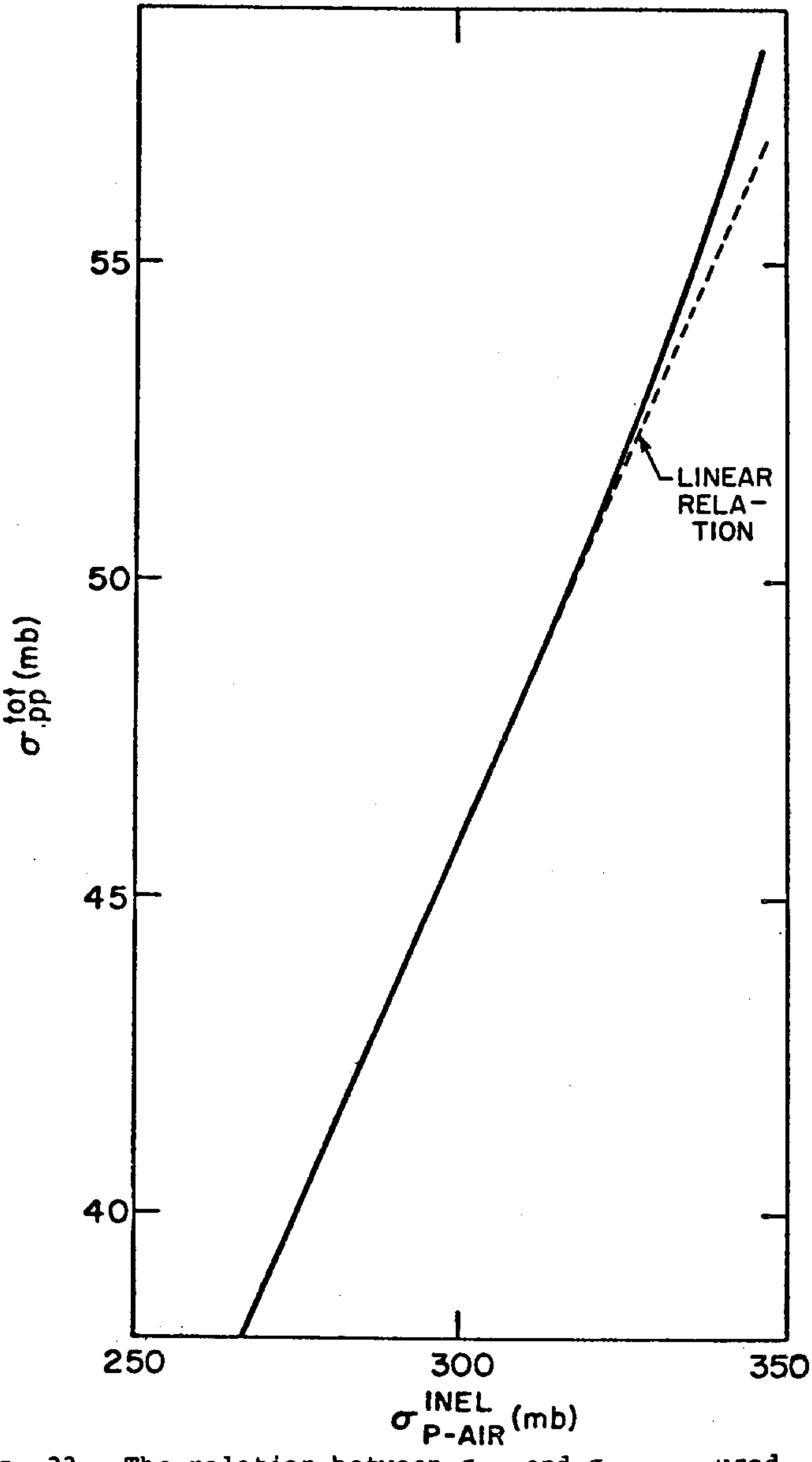

Fig. 33. The relation between σ_{pp} and σ_{p-air} used in Ref. 33 and justified by Glauber theory. There is no significant deviation from a linear relation for $\sigma_{pp}<54$mb. which is equivalent to $P_{Lab}<10^5$GeV.